

## What makes a city liveable?

Leach, J M; Lee, Susan; Braithwaite, Peter; Bouch, Christopher; Grayson, Nick; Rogers, Christopher

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# Infrastructure for a Better Future: A Forum for Vision, Leadership and Action



International Symposium for

# Next Generation Infrastructure

## Conference Proceedings

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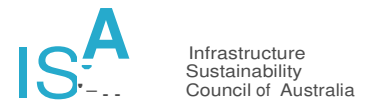
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# About SMART Infrastructure Facility



Australia, like many of its international peers is grappling with very difficult questions about the future provision of infrastructure. The way we have settled our communities and developed industries

in the past 100 years with an abundance of land, low population densities, scant attention to the environment and very modest community involvement all belongs to the past.

The SMART Infrastructure Facility is one of the largest research institutions in the world, funded by the Federal Government of Australia, NSW Government and University of Wollongong. It is dedicated to mapping out new data, concepts and frameworks to help governments, business and the community be more front-footed in the planning, funding and management infrastructure networks for our cities and regions.

Our goal is to ensure infrastructure can be designed, procured, funded and managed for the betterment of our nation by enhancing Australia's future global competitiveness, well-being of its citizens and resilience of its systems to natural and man-made events. It

is these matters that are the subject of an intensive global collaboration where SMART works alongside government, industry and academic institutions to help ensure better long term performance of brownfield and new infrastructure assets and systems

With its world-class laboratories, SMART can generate powerful and scalable models of national, regional and city-wide infrastructure networks, such as road, rail, water, energy and communication. This enables scenario planning of population changes on infrastructure networks and impact on performance over time.

SMART can deploy small and large-scale research teams and can access the expertise of University of Wollongong high degree students and academics.

SMART is set up to champion high quality and purposeful collaborations with industry and government in Australia and around the world to address key infrastructure challenges and assist with problem solving using evidence based computational tools.



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# Agency in Transport Service: Implications of Traveller Mode Choice Objective and Latent Attributes Using Ransom Parameter Logit Mode

A.M. Anwar<sup>a\*</sup>

K. Tieu<sup>a</sup>

P. Gibson<sup>a</sup>

K.T. Win<sup>a</sup>

M.J. Berryman<sup>b</sup>

**Abstract:** This paper explains how principal-agent theory (PAT) can be used as an analytical tool to understand the traveller-Transport for NSW (TfNSW) relationship and minimise the agency problem in the relationship by examining traveller preferences for mode choices. The paper emphasises latent variables (LVs) and traditional objective attributes (TOAs) together during the choice process within the agency relationship, as a method by which the utility of the principal (traveller) can be maximised and evaluated using a discrete choice experiment, i.e. random parameter logit (RPL) model. The probability of car use is significantly higher than public transport, which indicates that an agency problem exists in the relationship and incorporating traveller preferences in the transport projects may minimise this problem.

**Key words:** PAT; Traveler; TfNSW; LVs; TOAs; RPL Model; Mode Choice.

## I. Principal-Agent Theory and Agency Problem

PAT mainly focuses on the agency relationship between two parties. A relationship between two parties is understood when they involve in an association wherein one party (the principal) entrusts task and/or work to another party called agent to act on its behalf<sup>1,2</sup>. The important assumptions underlying PAT are that:

- Potential goal conflicts exist between principal(s) and agent(s);
- Each party acts in its own self-interest;
- Informational asymmetry frequently exists between principals and agents; and
- Agents are more risk averse than the principal.

Informational asymmetries and goal conflicts constitute the agency problem. This problem is appeared while the agent behaves opportunistically in such a way that works against the welfare

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<sup>a</sup> Faculty of Engineering and Information Sciences, University of Wollongong NSW 2522, Australia.

<sup>b</sup> SMART Infrastructure Facility, University of Wollongong NSW 2522, Australia.

\*Corresponding author: Mehbub Anwar [ahmma324@uowmail.edu.au](mailto:ahmma324@uowmail.edu.au).

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of the principal<sup>3</sup>. The agency problem may arise in situations in which the principal cannot directly observe the agent's actions and when the self-interested agent pursues his private goals at the expense of the principal's goals<sup>4,5</sup>.

## **II. Traveler and TfNSW Relationship**

Travellers have various kinds of preferences for their mode choice and the TfNSW has the capability to realise and address them. Due to experiences and skills of TfNSW, TfNSW is reasonably effective agent to fulfil the goals/expectations entrusted by travellers. The tax and travel fares paid by the citizens (travellers) are the source of funding of TfNSW, and travellers expect that TfNSW should perform on behalf of them. Therefore, the awareness about the traveler attributes, and maximisation of benefits has become the key issues in the discussion of the traveler-TfNSW relationship.

Provision of public transport (e.g. bus, train etc.) for travellers is one of the most important tasks of TfNSW who implements them with the help of transport operator. It is important to draw attention on the traveler choice attributes while providing services by TfNSW because TfNSW performs them at the traveler expenses. The public transport service should be as travellers demand to compete with their private car. Travellers are comfortable to use their own car and it makes complex situation in transport system for applying PAT. There is a conflict in choice and it is necessary to investigate the choice attributes towards the probability of mode use to find out the actual intention of travellers.

The role of TfNSW (agent) is to maximise the utility of the traveler (principal) within available resources. To realise the utility function of travellers to mode choice, TfNSW should have information about the nature of traveler's desires and demands. Thus, a metaphorical relationship is established in between traveler and TfNSW as indicated in PAT. In view of this relationship, the need to maximise travellers' utility is, therefore, important to examine travellers' preferences for various attributes of the modal choice. Travellers may not trust the quality of services performed by the TfNSW, because of its tendency to focus on its internal goals and opportunistic behaviour as opposed to more direct measures of the principals' goals.

To analyse the nature of traveller-TfNSW relationship, three hypotheses related to the travellers' (principals) preferences (both latent and observed) for modal choice attributes are generated and tested in this paper. Particularly, the relative importance of attributes related to traveller – TfNSW relationship, and how traveller preferences vary by socioeconomic and trip characteristics along with level of service and latent preferences, are examined by applying a series of RPL models.

## **III. Hypotheses**

To understand the traveller-TfNSW relationship, three hypotheses have been identified from the travel behaviour literature<sup>6-15</sup>. They are:

**Hypothesis 1 (H1):** Traveller preferences influence TfNSW's decisions on modal services.



**Hypothesis 2 (H2):** Individual specific attributes affect TfNSW's planning of modal services.

**Hypothesis 3 (H3):** Mode specific attributes and nature of trips have an effect also on TfNSW's decisions on modal service.

#### IV. Data

The key data source of this study was cross-sectional 2008/09 household travel survey (HTS) data. This is the largest and most comprehensive household travel survey of Sydney conducted by the Bureau of Transport Statistics (BTS) of Transport Department, New South Wales (NSW). BTS conducted a household questionnaire survey in four areas: Sydney, Newcastle and Illawarra and collected four types of data: household data, person data, trip data and linked trip data. For this particular study, only 'Sydney' and 'person data' have been taken into consideration for data analysis. Data collected from 82121 trips were used in this analysis as a sample size.

Six LVs and thirteen objective attributes have been evaluated to determine the impact on travellers' mode choice with the adequacy of objective attributes reflecting LVs. Latent variables are: (i) comfort, (ii) convenience, (iii) safety, (iv) flexibility, (v) reliability, and (vi) satisfaction and twenty indicators described in Table 1 were set to explain them. The thirteen explanatory variables (TOAs) are under three categories:

- 1) Level of services (LOS): travel time (in minutes), travel cost (in Australian dollars), waiting time (in minutes);
- 2) Socio-economic characteristics (SEC): age (in years), personal annual income (in Australian dollar), family size, gender (1 if male, 0 otherwise), car ownership per adult, having children (0-14 years), and number of full time workers of household; and
- 3) Trip characteristics (TC): trip rate (trip per person per day), trip purpose (1 if work, 0 otherwise) and distance travelled (in kilometre).

The following is the list of psychometric indicators (Table 1) that were considered in the modelling approach of this study for structuring the influence of LVs in traveller preferences.

**Table 1. Description of latent variables.**

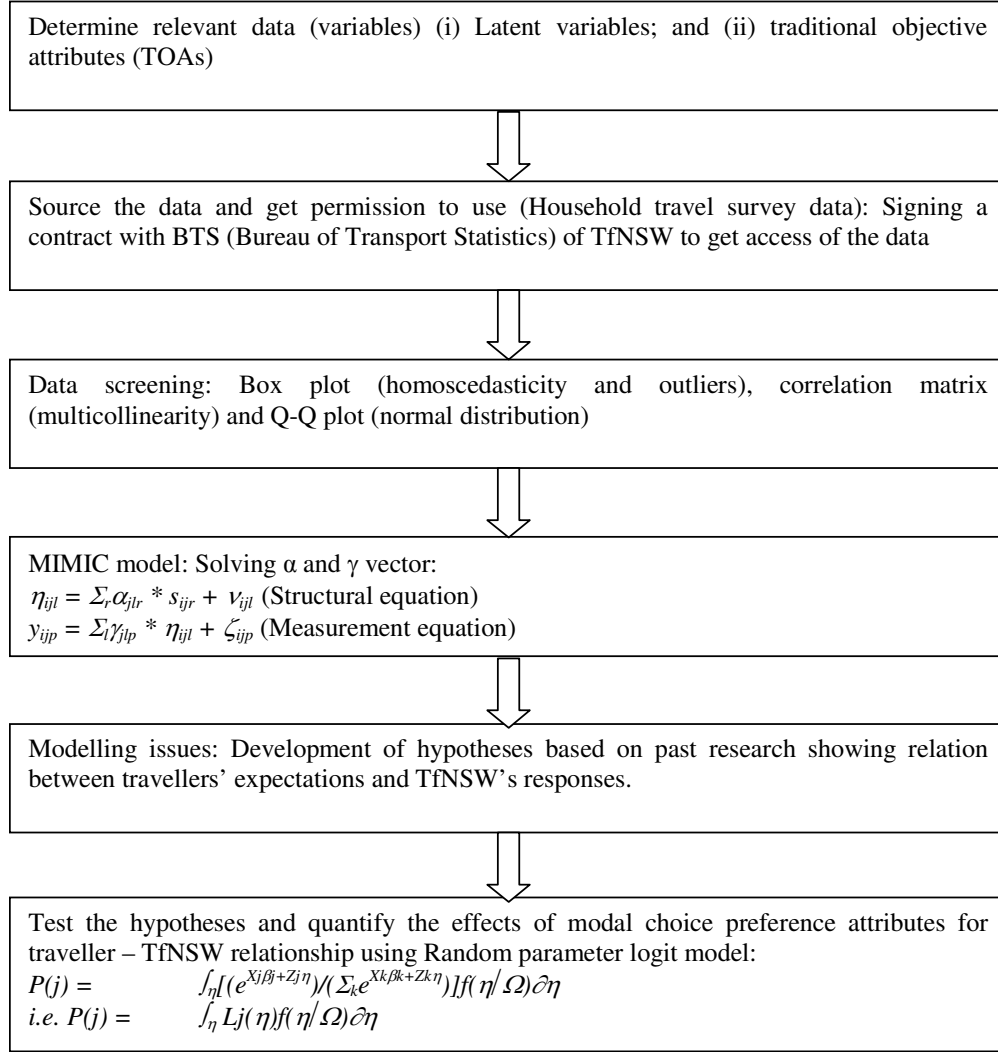
<i>Latent factors</i>	<i>Explained by (indicators)</i>	<i>Definitions</i>
Comfort	- Enjoy time to read/relax on vehicle	Importance with 1, otherwise 0
	- Stressfulness on vehicle	Importance with 1, otherwise 0
	- Service slower	Importance with 1, otherwise 0
Convenience	- Mode availability	Importance with 1, otherwise 0
	- Accessibility (does not go where required)	Importance with 1, otherwise 0

	- Timetable availability	Importance with 1, otherwise 0
Safety	- Safety response for mode used in 1 <sup>st</sup> trip	Importance with 1, otherwise 0
	- Safety response for mode used in 2 <sup>nd</sup> trip	Importance with 1, otherwise 0
	- Safety response for mode used in 3 <sup>rd</sup> trip	Importance with 1, otherwise 0
Flexibility	- Fixed start and finish times – each day can vary	Importance with 1, otherwise 0
	- Rotating shift	Importance with 1, otherwise 0
	- Roster shift	Importance with 1, otherwise 0
	- Variable hours	Importance with 1, otherwise 0
Reliability	- Frequency	Importance with 1, otherwise 0
	- Punctuality	Importance with 1, otherwise 0
	- Faster	Importance with 1, otherwise 0
Satisfaction	- Cleanliness	Importance with 1, otherwise 0
	- Travel time	Travel time in minutes
	- Travel cost	Travel cost in Australian dollar
	- Waiting time	Waiting time in minutes

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## V. Steps and methods of the study

There are two approaches available for incorporating LVs into the choice models (i) sequential (also known as two-step) approach, where the LVs are needed to be constructed before being included into the discrete choice model as regular explanatory variables<sup>16,9</sup>, and (ii) the simultaneous approach, where both processes are done simultaneously<sup>7,17</sup>. The two-step approach is performed to estimate the results in this paper.



**Figure 1. Workflow of this study.**

Figure 1 shows the work flow/steps of this study and it clearly explains the evaluation steps of preference attributes both from traveller and transport mode perspective leading to the travellers' choice of a mode of transport. Travellers pay more importance for the preferable attributes for selecting the modal service and therefore, TfNSW should perform the entrusted services at reasonable manner as per travellers demand which form a metaphorical relationship (contract) as indicated in PAT. In practice, different types of modes are available to travellers and they choose the mode considering the perceived service quality acted by the TfNSW. The nature of the traveller – TfNSW relationship within modal choice can also influence traveller satisfaction with the degree of better services provided by TfNSW. A MIMIC (multiple indicators and multiple causes) model is used to test the reliability of latent variable indicators and to solve the  $\alpha$  and  $\gamma$  vector matrix in structural and measurement equations respectively in Figure 1. These vector matrixes are useful to quantify the effect of LVs and validate the indicators of LVs respectively. The information obtained from MIMIC mode has been used in a random parameter logit (RPL) model, which can overcome the problem of independence of irrelevant alternatives

(IIA) and independent and identically distributed (IID) assumptions because of addition an additional random term in the function as stochastic component.

## VI. Empirical Results

Reliability of the indicators listed in Table 1 was tested using factor analytic models (exploratory and confirmatory factor model). The factor analytic model focuses solely on how, and the extent to which, the observed variables are linked to their underlying latent factors<sup>18</sup>. However, due to the limited space allocation for this paper, the outcomes of  $\alpha$  vector matrix in structural equation and  $\gamma$  vector matrix in measurement equation are not presented here. For further details, please see Anwar et al.<sup>19</sup>.

Table 2 discusses the results obtained from RPL models. The models were estimated in LIMDEP (Nlogit 4), econometric software, using maximum likelihood estimation procedures. A series of four RPL models were estimated with considering TOAs and LVs. Only LOS attributes are included in TRPL1. Then LOS and SEC are considered in TRPL2 model. In TRPL3 model, all TOAs have been incorporated simultaneously and finally, HRPL explains the impact of TOAs and LVs together.

Interestingly it is observed that significance level of RPL2 is stronger than RPL1 and RPL3 is stronger than RPL2. It indicates good explanatory power of the models while a number of relevant attributes is included in the model. Here, the model statistics indicate that the hybrid RPL model is the best model because LVs are integrated into the model, which provides valuable insights into the motivational processes to mode choice. Results confirm that travel time, waiting time, travel cost, and car ownership among TOAs, and safety and reliability among LVs are mostly leading and significant predictors of mode choice. Further understanding is that the desire for comfort and convenience positively impacts commuter mode choice. It is noted that due to the inclusion of LVs, the effects of TOAs are decreased substantially and in that sense delivered true additional insight. Considering LVs, it is observed that likelihood of train use has been increased though still car use as a driver is dominant. In contrast, as the probability of bus usage is declining, bus companies need to improve the services as traveller demands and thus the agency problem might be minimised. From the results, since the probability of car use is significantly high in comparison to public transport use, the agency problem persists in the traveller-TfNSW relationship. This study has shown then that the integration of LVs in transport mode related projects undertaken by TfNSW is imperative to resolve the agency problem.

**Table 2. Results of random parameter logit models (t-values within the parenthesis).**

Attributes	TRPL <sup>1</sup>	TRPL <sup>2</sup>	TRPL <sup>3</sup>	HRPL
<b>Random parameter in utility functions</b>				
Travel cost (mean)	-3.14(-2.11)	-3.19(-2.56)	-3.20(-5.55)	-2.11(-2.62)
Travel cost (st.dev.)	1.07(1.99)	1.02(2.45)	1.05(3.45)	1.06(4.21)
Waiting time (mean)	-1.72(-2.12)	-1.85(-3.11)	-1.93(-3.15)	-1.75(-3.14)
Waiting time (st.dev.)	0.08(3.11)	0.03 (3.41)	0.004(2.48)	0.004(2.99)
Age (mean)		-0.22(-1.89)	-0.11(-1.11)	-0.09(-2.84)
Age (st.dev.)		0.48(1.66)	0.22(2.01)	0.58(2.63)
Car ownership (mean)		1.84(3.52)	1.91(5.21)	1.89(4.00)
Car ownership (st.dev.)		0.03(3.51)	0.02(4.21)	0.04(4.44)

Attributes	TRPL <sup>1</sup>	TRPL <sup>2</sup>	TRPL <sup>3</sup>	HRPL
Having children (mean)		-1.78(-6.44)	-1.80(-5.41)	-1.77(-5.02)
Having child (st.dev.)		0.11(3.65)	0.26(3.11)	0.12(2.87)
Trip purpose (mean)			0.07(3.44)	0.06(2.15)
Trip purpose (st.dev.)			0.003 (2.33)	0.001(3.63)
Comfort (mean)				3.32(7.89)
Comfort (st.dev.)				0.12(5.66)
Convenience (mean)				3.18(4.66)
Convenience (st.dev.)				0.22(5.66)
Safety (mean)				5.18(11.11)
Safety (st.dev.)				0.45(9.84)
Flexibility (mean)				0.73(1.00)
Flexibility (st.dev.)				0.30(2.16)
Reliability (mean)				5.17(11.10)
Reliability (st.dev.)				0.01(9.15)
Satisfaction (mean)				1.23(2.66)
Satisfaction (st.dev.)				0.09(2.99)
<b>Nonrandom parameter in utility functions</b>				
Age	-0.08(-0.99)			
Having children under 5 yrs	-0.97(-3.62)			
Car ownership	1.27(3.91)			
Trip purpose	0.97(2.89)	0.97(2.91)		
Travel time	-1.17(-7.85)	-1.17(-8.77)	-1.19(-6.42)	-1.11(-3.63)
Gender	0.29(1.89)	0.32(2.13)	0.39(2.15)	0.21(2.69)
Income	1.32(1.85)	1.69(1.11)	1.98(1.91)	1.50(0.89)
Family size	-0.94(-0.45)	0.94(1.01)	0.93(0.99)	0.94(1.00)
Full time workers of HH	0.97(0.32)	0.97(1.45)	0.97(0.85)	0.97(1.01)
Trip rate	0.91(1.11)	0.91(1.00)	0.91(1.74)	0.91(1.86)
Distance travelled	-0.19(-1.89)	-0.17(-1.11)	-0.78(-1.01)	-0.24(-1.12)
<b>Mode constant</b>				
Car as a passenger (base)	0	0	0	0
Car as a driver	-2.22(-2.45)	-2.23(-2.54)	-2.22(-3.10)	-2.41(-9.00)
Train	-1.00(-1.99)	-1.17(-1.98)	-2.18(-3.41)	-2.39(-7.15)
Bus	-0.11(-0.52)	-0.12(-1.23)	-0.14(-1.22)	-0.10(-1.53)
<b>Heterogeneity around the mean</b>				
Travel cost :Income	-0.11(-4.21)	-0.10(-2.98)	-0.12(-3.62)	-0.01(-3.99)
Waiting time :Income	-0.54(-3.56)	-0.54(-2.56)	-0.54(-2.96)	-0.03(-3.85)
Age: Income		-0.11(-1.89)	-0.08(-1.98)	-0.12(-2.14)
Car ownership: Income		0.02(3.12)	0.01(3.01)	0.65(5.14)
Having child: income		-0.02(-1.99)	-0.09(-2.66)	-0.17(-3.01)
Purpose: Income			0.01(4.01)	0.05(3.01)
Comfort: Income				0.09(3.10)
Convenience: Income				0.10(2.89)
Safety: Income				0.45(11.52)
Flexibility: Income				0.05(2.45)
Reliability: Income				0.31(10.20)
Satisfaction: Income				0.08(5.10)
<b>Model statistics</b>				
Log likelihood function	-812.41	-768.31	-715.28	-613.37
McFadden Pseudo R-squared	0.21	0.25	0.27	0.36
Akaike Information Criterion (AIC)	0.019	0.018	0.017	0.014
<b>Modal choice probability</b>				
Car as a driver	0.713	0.721	0.731	0.785

Attributes	TRPL <sup>1</sup>	TRPL <sup>2</sup>	TRPL <sup>3</sup>	HRPL
Car as a passenger	0.080	0.075	0.055	0.010
Train	0.159	0.160	0.181	0.190
Bus	0.048	0.044	0.033	0.015

**Legend:**

**Significant at 90% level of confidence if  $1.960 > t \geq 1.645$ ;**

**Significant at 95% level of confidence if  $2.576 > t \geq 1.960$ ;**

**Significant at 99% level of confidence if  $2.810 > t \geq 2.576$ ;**

**Significant at 99.5% level of confidence if  $3.290 > t \geq 2.810$ ;**

**Significant at 99.9% level of confidence if  $t \geq 3.290$ .**

## VII. Discussions and Conclusions

The HRPL mode is more powerful than the TRPL model. It indicates that the LVs dominate the traveller choice process and TfNSW should aware about the travellers' dominating behavioural nature otherwise agency problem will continue. Therefore, the analysis of the traveller-TfNSW relationship is also relevant in the context of transport policy responses.

As a response to the agency problem (lack of awareness about travellers' utility functions) caused by goal conflicts in the traveller-TfNSW relationship, the policy response suggested that awareness about travellers' expectations should be concerned and addressed by TfNSW. Transport planners realise the importance of TfNSW measuring travellers' latent preferences in modal services, however little attention has been paid to the nature of such a policy response. This study has partly clarified the nature of such a policy response by indicating which attributes of the traveller-TfNSW relationship are most important to travellers.

With the analysis of exploring this relationship, it is understood that traveller's preference to mode choice is a fundamental factor and it supports TfNSW for the provision of effective and successful services. It seems that the process of response acted by TfNSW towards travellers' desires is highly complex. This paper simplifies the response mechanism so that the transport policy makers can incorporate the findings of this study into the future project. On the other way, to ration limited resource of TfNSW effectively, TfNSW needs to be aware of those attributes of travellers' choice process that should increase travellers' utility the most. Thus, the maximisation of traveller's utility helps to rectify the agency problem.

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# **London Overground – A success story: Transforming neglected urban railway infrastructure to meet capacity and connectivity demands**

N. Badstuber<sup>a</sup>  
C. Smales<sup>b</sup>

**Abstract:** London Overground illustrates the successful transformation of underused and fragmented urban railway infrastructure into an orbital service boasting record passenger satisfaction and popularity. London's metropolitan transport authority Transport for London achieved this through a combination of measures. In addition to station upgrades and new trains, the provision of integrated transport services, such as integrated ticketing and customer information, marketing and branding contributed to London Overground's success. In 2007, Transport for London took over the concession to operate and manage the neglected railway routes. Since then, London Overground has become one of best performing train operators in Great Britain. London Overground patronage has nearly quadrupled since Transport for London took over the management of the concession – surpassing demand forecasts and necessitating further capacity enhancement investment. As well as providing new radial connections, London Overground has also managed to attract passengers from London Buses, National Rail and London Underground, and thereby freed capacity on these stressed services. This paper will describe all of these transformations and draw out some principles that will be of use to other similar initiatives.

**Key words:** Railway; Infrastructure; Regeneration; Connectivity; Orbital transport; London overground; Transport for London.

## **I. Introduction**

London's public transport authority Transport London has successfully transformed neglected and fragmented urban rail infrastructure into a comprehensive network that complements the existing public transport provision in London. An inner London orbital service was created by Transport for London by linking up a dispersed and fragmented collection of railway routes. This network was branded as London Overground and became part of Transport for London.

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<sup>a</sup> Department of Civil, Environmental and Geomatic Engineering, University College London, London WC1E 6B, UK

<sup>b</sup> London Rail Development, Transport for London, London, SE1 8NJ, United Kingdom  
<http://dx.doi.org/10.14453/isngi2013.proc.3>

The largest component of the new London Overground network is formed from the previous Silverlink Metro routes. Transport for London took over the management of the Silverlink Metro concession in November 2007<sup>1</sup>. Silverlink Metro ran suburban and inner London services from Stratford to Richmond, Willesden Junction to Clapham Junction, London Euston to Watford Junction via Willesden and Gospel Oak to Barking. The map below illustrates the former Silverlink Metro rail routes rebranded as London Overground.

The Silverlink Metro ran a low quality service, marked by neglected stations, old rolling stock and low service levels. When taking over the concession Transport for London set about transforming the network with a programme dedicated to the enhancement of the level and quality of services which included:

- New rolling stock
- Upgraded infrastructure to accommodate higher service levels
- Station refurbishments
- High standards of customer service<sup>1</sup>

### London Overground network map

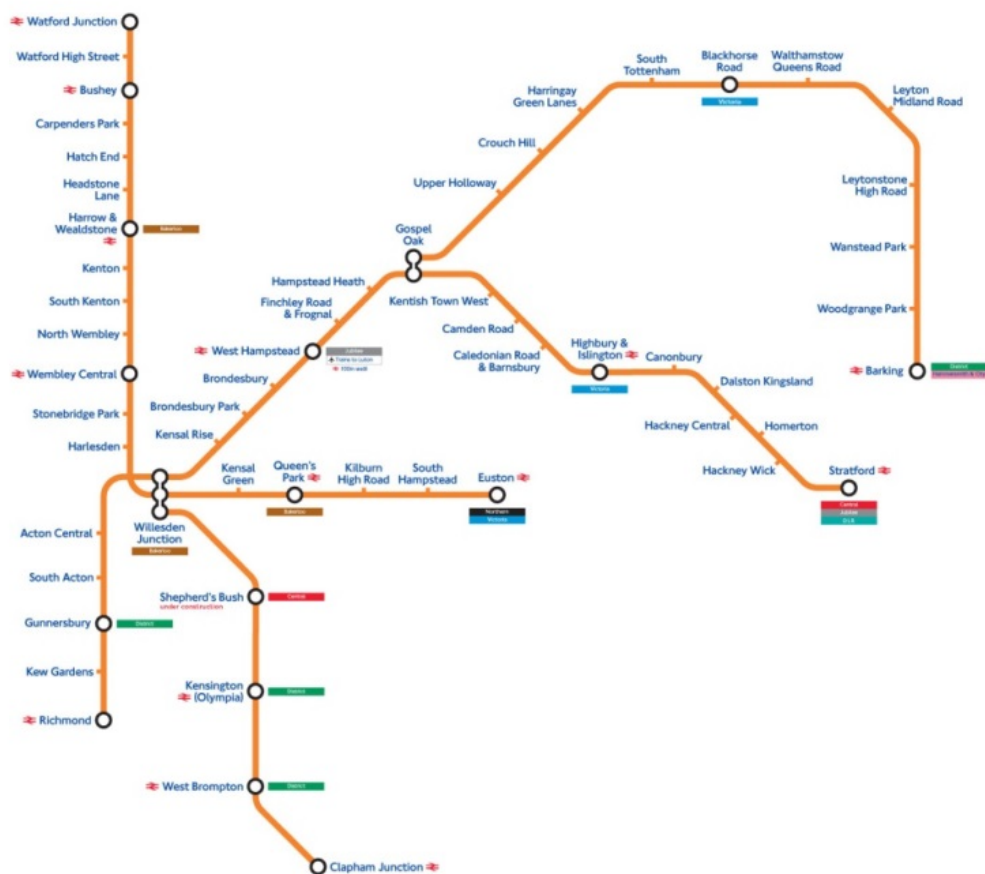
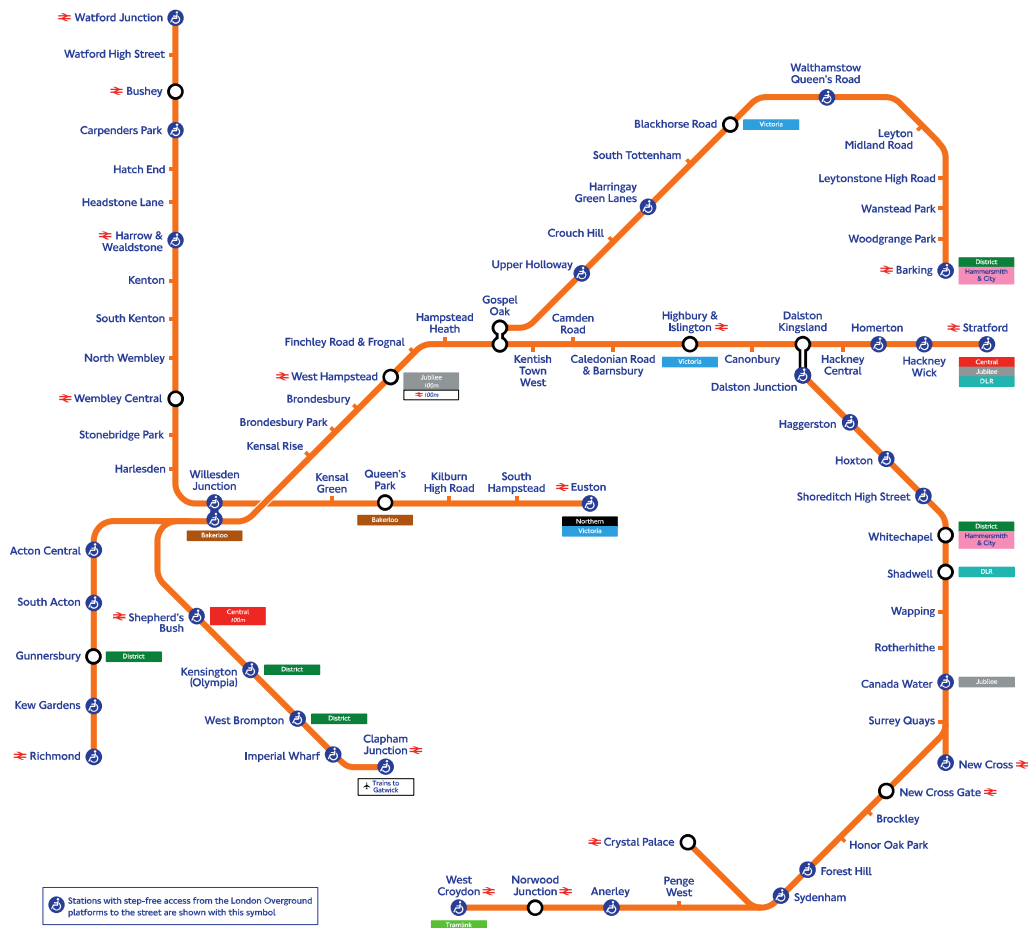


Figure 1: London Overground Network in 2008<sup>2</sup>



**Figure 2: London Overground Network in 2011 (with East London Line Extensions<sup>5</sup>)**

### A. East London Line

Another existing route to be integrated into the London Overground was the London Underground East London line from Whitechapel to New Cross Gate<sup>3</sup>. The East London Line was closed in 2007 to become part of the London Overground network. The infrastructure of the former London Underground East London Line needed to be upgraded to accommodate the new levels of service. The work involved the installation of new signaling and communications equipment as well as the replacement of tracks and construction of new bridges. In the same fashion as the former Silverlink Metro stations, all existing stations were refurbished to offer modern and high level of customer service and experience.

The East London line was extended both to the north, to meet the Richmond to Stratford line at initially only to Dalston in 2010 and later Highbury & Islington in 2011, and to New Cross,

Crystal Palace and West Croydon via separate branches in the South<sup>1,4</sup>. The section north of Whitechapel uses the route of the old railway lines into Broad Street station, which was closed in 1986. Along this section four new stations were constructed. The section south of New Cross Gate runs alongside the existing mainline railway tracks<sup>3</sup>. A full service between Highbury & Islington and New Cross/Crystal Palace/West Croydon via the City opened on 28 February 2011<sup>4</sup>. A map capturing the expanded network to the East and South East is shown below.

## B. Completing the Orbital

The orbital was completed with the final link currently planned on the London Overground network in December 2012. London Overground's newest addition is an extension across south London between Surrey Quays and Clapham Junction station. Four new stations were built along the route. Thereby, offering a new level of connectivity to the residents along the route<sup>4</sup>. The complete transformation of neglected a fragmented urban rail infrastructure into the orbital London Overground network to date cost Transport for London £1.5 billion<sup>4</sup>.

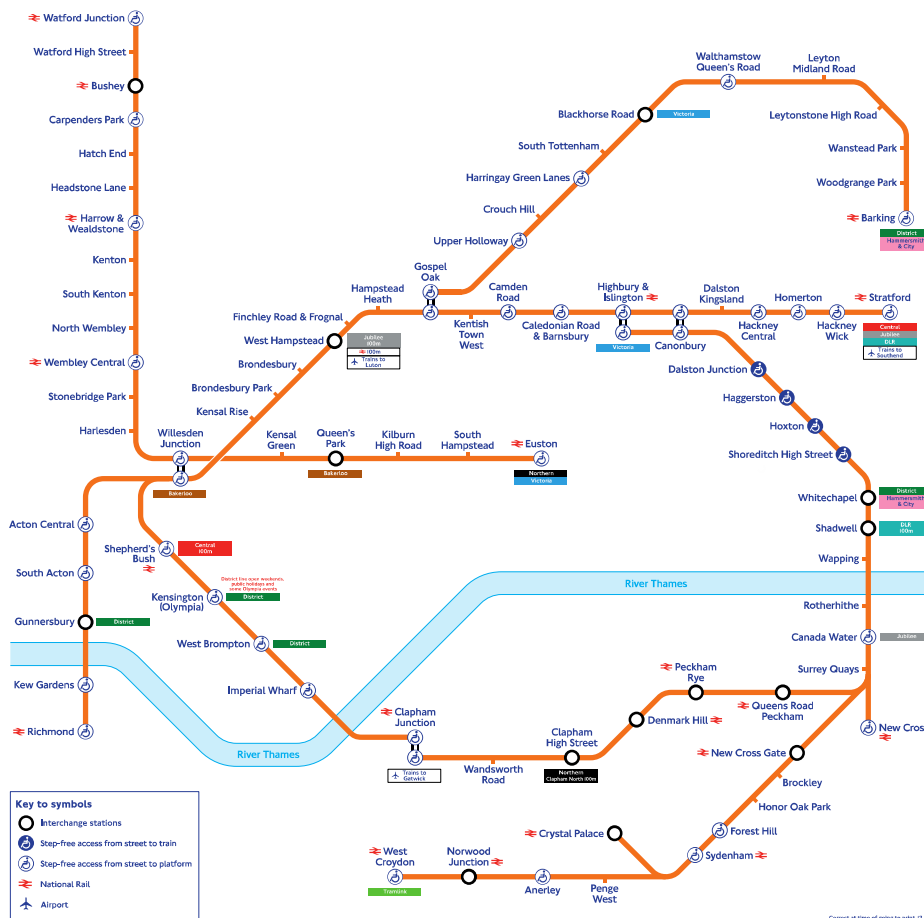


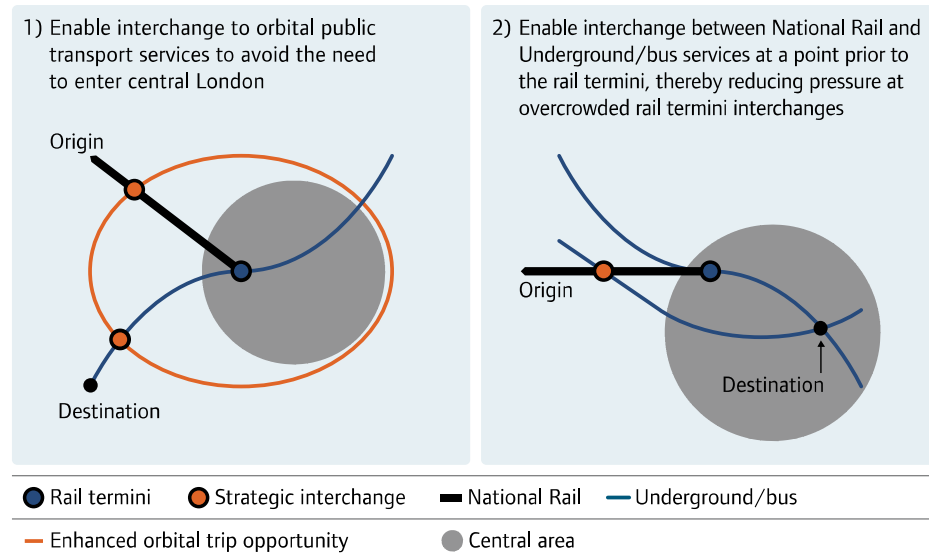
Figure 3: London Overground Network as of December 2012<sup>6</sup>

### C. Alignment with the London Plan and Mayor's Transport Strategy

The London Plan is an overall strategic plan for the UK capital which sets out an integrated social, economic, environmental and transport framework for development in London for the next twenty years<sup>7</sup>. The London Plan was developed alongside the Mayor's Transport Strategy, in which the Mayor of London sets out his vision for transport in the next twenty years. With high levels of residential and employment migration into London, 1.25mil and 0.75mil respectively by 2031, sustainable transport is the key keeping London moving<sup>8</sup>. Alongside this significant population growth rail demand is forecast to grow by two-thirds by 2031<sup>9</sup>. This will inevitably put pressure on the transport network, leading to greater crowding levels and thereby adversely affecting both journey times and reliability. The public transport network is vital to keeping London moving. Urban rail in particular carries 80% of all journeys into London<sup>9</sup>. London Overground is therefore vital to providing greater capacity and offering alternative routes in order to relieve capacity in Central London<sup>9</sup>. One of the ways the London Plan proposes to enhance London's transport connectivity is to provide an orbital rail network, i.e. London Overground, which would support future development, regeneration of priority areas and increase public transport capacity.

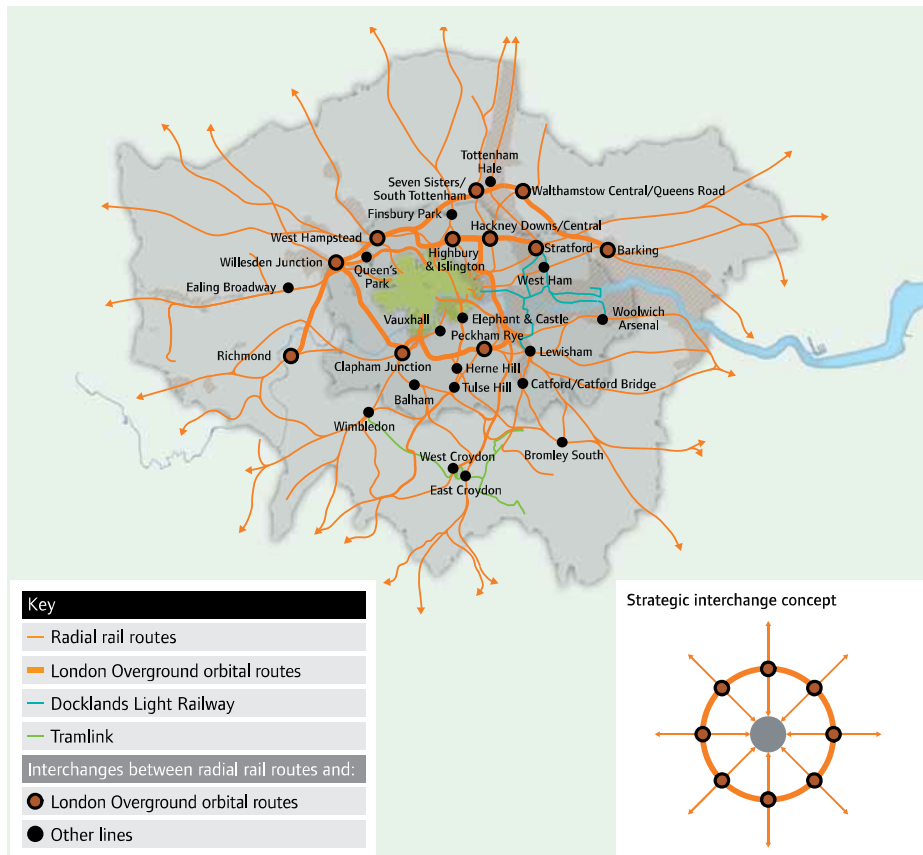
London Overground's orbital service complements the existing services by providing links between inner London areas without customers needing to travel via central London. London Overground facilitates strategic interchanges between orbital and radial routes. The concept of these strategic interchanges is outlined in the Mayor's Transport Strategy<sup>10</sup>.

Strategic interchanges will help to relieve passenger dispersal pressures at central London rail termini through two primary means:



**Figure 4: Strategic Interchange Concept<sup>10</sup>**

Interchanges expand the level of accessibility to opportunities and services as well as improve connectivity and passenger journey experiences. Strategic interchanges outside of central London have the potential to reduce travel times for the individual customer and relieve crowding in central London. Key to achieving these goals is the quality of the interchange. To achieve world-class interchanges which encourage multi-modal public transport use and attract passengers from using their private cars Transport for London has published Interchange Best Practice Guidelines<sup>11</sup> to ensure high quality and effective interchanges across their jurisdiction. As part of the Transport for London family, London Overground stations were also designed to ensure customers would have a good interchange experience.



**Figure 5: Examples of Strategic Interchange Locations Outside Central London<sup>10</sup>**

As you can see in the figure above the London Overground provides the backbone potential radial orbital interchanges, improving journeys for customers through reduced journey times and freeing up capacity at Central London interchanges.

## II. Success of London Overground

### A. Passenger Numbers

London Overground patronage tripled in the four years following Transport for London's take-over of the concession, between November 2007 and 2011. A large part of the growth occurred on the East London Line with its new extensions. However, the rest of the London Overground network also experienced passenger numbers increasing by 110%<sup>1</sup>. Today, four

times as many passengers are using London Overground than before the concessions were taken over. The latest four week period (Period 3 for 2013/2014) was the busiest for the London Overground to date with 10.9 million passengers<sup>12</sup>.

Peak services are already crowded. In 2009, new high capacity trains were introduced and in 2011 the service frequency was doubled<sup>13</sup>. The popularity of the service is highlighted by demand for the service having grown in line with capacity increases. Demand for the services has increased steadily. London Overground has already completed an additional capacity enhancement programme since it's initial upgrades. In 2010 the train capacity was increased by over a third by adding an additional car to the train along the North and West London Line. Initially only three car trains were introduced, these were extended to four car trains already in use on the East London Lines in 2010<sup>1</sup>. The crowding levels today match those recorded before these two measures were implemented. By 2016, as illustrated below, it is anticipated that demand will exceed Transport for London's planning standard of no more than three passengers per square metre standing in the morning peak<sup>1</sup>. Demand across the whole London Overground network alone is expected to increase by another forty per cent by 2021<sup>15</sup>.



**Figure 6: Forecasted Crowding on London Overground in 2016<sup>1</sup>**

The fastest growing section of the network has been on the Willesden to Clapham Junction route between the two new stations along that route: Shepherd's Bush and Imperial Wharf. Shepherd's Bush now provides links with London Underground's Central Line as well as easy access to a large urban shopping mall<sup>1</sup>. Imperial Wharf station has provided new levels of connectivity to an area previously underserved by public transport. The popularity of the service along this section has outstretched capacity already. These two sections are the busiest sections along with the Highbury & Islington to Dalston section. Crowding in the peak surpasses



the crowding levels Transport for London designs for, namely three passengers per square metre. The London Overground Loadweight<sup>12</sup> report from the weeks commencing the 10th and 17th June 2013 indicates that crowding levels of up to 6 passengers per square metre standing are reached close to passenger safety crowding threshold of 7 per square metre. Maximum train loading is considered 5 passengers per square metre – which these peak services are exceeding – and 7 passengers per square is considered *crush load*<sup>14,15</sup>. Peak loads are increasing necessitating further capacity investment.

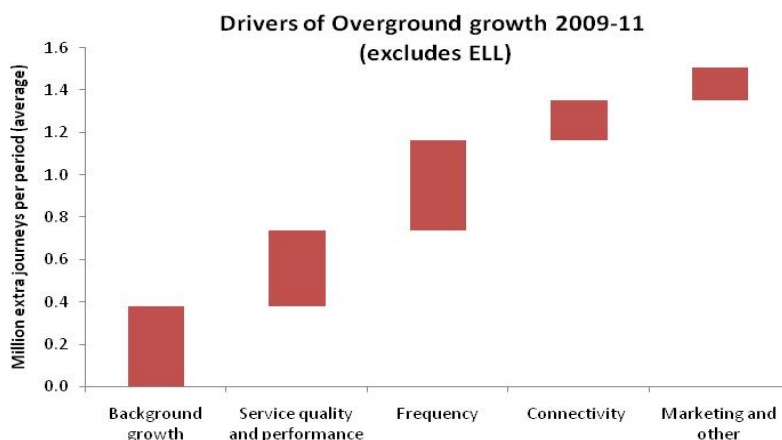
The popularity of the link demonstrates the former gap in public transport provision that the London Overground has managed to fill. It is servicing new areas and providing easy connections between previously underserved routes. The popularity of this section also highlights the importance of good interchange facilities which encourage customers to undertake multi-modal journeys to access new services and opportunities.

Transport for London will be increasing the number of cars on the routes using electric 4-car trains (all bar Gospel Oak to Barking on which diesel trains run) from four to five cars to further increase capacity on the lines. This London Overground capacity enhancement scheme will increase capacity by more than a quarter and thereby reduce crowding on trains. The scheme will first be rolled out to the East London Line, from Highbury & Islington to West Croydon/Clapham Junction, from December 2014. The rolling stock upgrade will follow on all other electric lines in 2015<sup>13</sup>. Transport for London has placed an order for 57 new cars with the original manufacturer Bombardier worth £88 million. This is part of a wider £320million capacity enhancement programme which also includes the construction of longer platforms, depot enhancement, new signalling and power works<sup>16,17</sup>.

## B. Drivers of Growth

Key drivers of rail demand are the economy, demographics, fares and service levels. During an economic downturn rail demand is therefore, assumed to slow. However, this has not been the case in London and South East of England. On the contrary, rail demand grew strongly between 2010 and 2012<sup>1</sup>. Instead, other drivers contributed to London Overground's growth in patronage, namely:

- Service frequency
- Operational Performance
- Service Quality, including stations and rolling stock
- Connectivity
- Marketing



**Figure 7: Drivers of Growth on London Overground**

The impact of each of these drivers to the overall patronage increase was calculated by Transport for London using industry elasticity to generate a waterfall chart, as depicted above<sup>1</sup>.

In the first instance, London Overground has benefitted from a buoyant rail market in London and South East England<sup>1</sup>. Despite the economic downturn rail usage has steadily increased. Background growth, however, has only contributed a quarter of the patronage increase observed on the routes between 2009 and 2011. The largest contributor to London Overground's growth was service frequency.

### C. Frequency

When Transport for London took over the concession from Silverlink Metro in 2007, up to six trains per hour ran between Stratford and Richmond and three trains per hour between Clapham and Willesden Junction. In the off peak frequencies were notably lower at four and two trains per hour respectively. There have been two updated timetables since the concession was taken on, one in 2010 and 2011. The frequency was changed to three trains per hour from Stratford to Clapham Junction and three trains per hour from Stratford to Richmond. The schedule was changed to service the increasingly popular link between Clapham and Willesden. In 2011, the service frequency was increased to four trains per hour on both routes<sup>1</sup>.

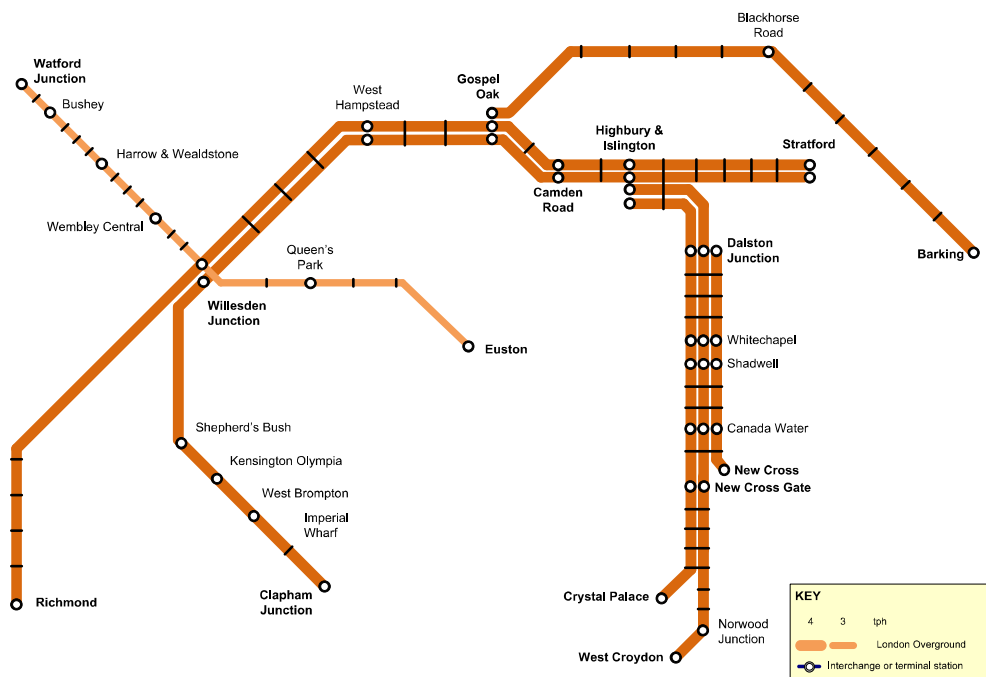


Figure 8: Frequency of London Overground Services<sup>1</sup>

Based on extensive research conducted for London Underground, Transport for London has set the frequency all stations should receive at least four trains per hour throughout the week, wherever appropriate<sup>9</sup>. The research demonstrated that this level of standardized frequency addressed customer preconceptions that the journey would be lengthy and inconvenient<sup>9</sup>. Instead the “turn up and go” service frequency encourages customer to use the service without planning their journey in advance, thereby attracting customer from other frequent services such as the bus and London Underground.

#### **D. Service Quality - New Trains**

All London Overground routes bar the Gospel Oak to Barking route are now served by a four car high capacity train. Longitudinal seating and walk-through carriages maximise capacity. The trains have a capacity of 700, designed to carry customers in comfort for short distances<sup>1</sup>. The suburban old rolling stock was replaced for a metro style rolling stock.

#### **E. Service Quality - Safe Stations**

During 2011, all London Overground stations were refurbished to provide a safe and secure station environment to customers. This was achieved through:

- Modernising stations
- Improving lighting
- Installing more CCTV
- Managing stations more effectively
- Visible policing and security patrolling
- Providing more Help Points
- Implemented alcohol and smoking bans
- Enhanced information systems
- Continuous station maintenance and cleaning<sup>9,13</sup>

The design principles developed by Transport for London’s dedicated team, Crime Prevention Through Environmental Design, were also applied to London Overground to *design out crime*<sup>13</sup>. The success of these efforts is captured by the Passenger Focus surveys<sup>18,19</sup> in which passengers self-assessment of their personal security whilst using the station increased by nearly thirty percentage points from a satisfaction level of 45% to 74% since Transport for London took over the concession. There were also significant increases in customer satisfaction in the overall station environment, for which the passenger satisfactions rates increased from 50% to 69% between Spring 2010 and 2011 - during this period a considerable number of stations underwent the station refurbishment as outlined above. The new maintenance and upkeep periodicity also received high customer approval rates. Passenger satisfaction rates went up with statistical significance by nearly 20% for the same time period with regard to cleanliness and station upkeep/repair of the station buildings and platforms<sup>18</sup>.

#### **F. Service Quality – Staff**

All London Overground stations are staffed while trains are running, to enable customers to access help from members of staff available. In additions this will also increase the safety at the stations<sup>20</sup>.

## **G. Branding**

London Overground has been branded with the same operational branding as the rest of Transport for London. A recognizable adaptation of the Transport for London roundel brand originally designed Edward Johnston for London Underground in 1918 has been adopted for London Overground<sup>21</sup>. The bright orange formerly used to denote the London Underground East London Line which was incorporated in the London Overground network was adopted for the London Overground with a roundel mirroring the London Underground icon with the red replaced with orange.

London Overground design standards were introduced to promote a high level of quality and consistency in appearance and all communications. London Overground design standards fall in line within the Transport for London family brand. To ensure the continuity and consistency in brand design separate London Overground design standards were developed for basic elements, signs, posters, the built environment, stationary and train graphics. The standardised appearance of the patchwork network was achieved with a design standard for stations. The adaptation of the roundel also implied a service quality and level that the customers are accustomed to from the other Transport for London brands. Supplementing the visual appearance with an higher service quality and frequency, increased maintenance regimes, improved customer service and Transport for London's smart card ticketing system, presented the London Overground network as a *fully-fledged* member of the Transport for London family both in terms of appearance and performance.

## **H. Marketing**

In addition to the rebranding of the stations and routes Transport for London took over they also had an active marketing campaign to raise awareness and encourage the use of the new network. In 2008, they launched a campaign called *London's New Train Set* which intended to inform passengers about the new London Overground network<sup>20</sup>. London Overground also appeared on the London Underground network maps in addition to its appearance on the London Rail maps. This placed London Overground firmly on the map for Londoners and visitors navigating the city. The "turn-up-and-go" service frequency enabled this as London Overground services were now a reasonable journey alternative.

The success of the marketing campaign is captured in the survey results of customer research conducted for London Overground East London Line<sup>22</sup>. Surveys were undertaken pre and post opening of the extended and refurbished line. Pre-opening 62% planned to use the service. Post opening a slightly smaller proportion 57% had already used it and an additional 19% planned to use it. In total 76% (89% and 61% of the survey users on rail and bus respectively) had used or intended to use the new service<sup>22</sup>.

## **I. Integrated Ticketing**

From when Transport for London took over the concession of the Silverlink Metro routes, the smart card ticketing already used on Transport for London's other services such as London Underground, London Buses and Tramlink could be used on the London Overground network<sup>20</sup>. The smart card ticketing facilitated and encouraged the use of the network and multimodal journeys. The smart card eliminated the barrier to using the service created by the need to purchase a separate ticket and the higher financial cost associated with of National Rail tickets.

Instead the Transport for London smart card offers customers the best fares and will cap at less than the price of an equivalent Day Travel Card or One Day Bus card if multiple journeys are undertaken in a 24-hour period<sup>20</sup>.

### J. Integrated Transport

An indication of the success of the integration principles applied to London Overground is the level of interchanging passengers from London Overground onto different other modes. In the London Overground Impact Study<sup>1</sup> it was identified that a fifth of London Overground passengers interchange with London Underground or Transport for London's light rail network the Docklands Light Railway. Another 20% interchange onto London Buses or other London Overground branches. This compares to half of all mainline railway passenger who switch onto London Underground or Docklands Light Railway in the morning peak when arriving in London<sup>1</sup>.

### K. Switch from other services

The largest share of passengers switched from using London Buses or London Underground to London Overground since Transport took over the management of the London Overground network.

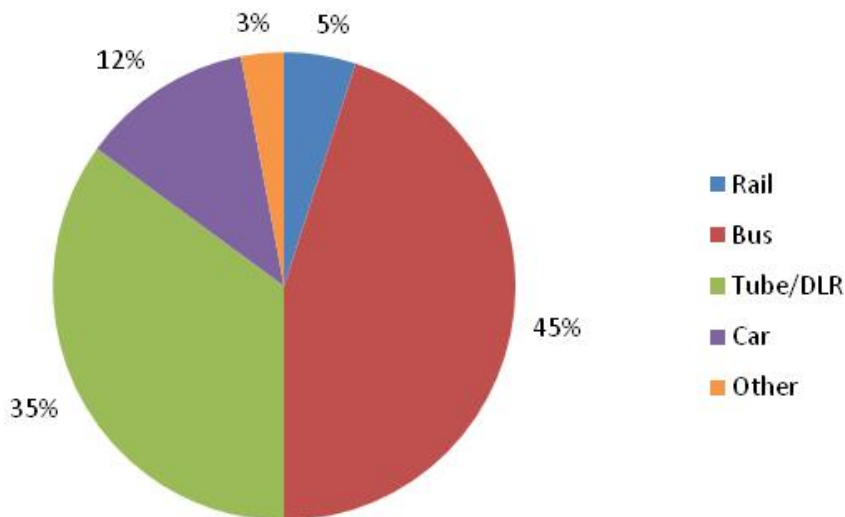
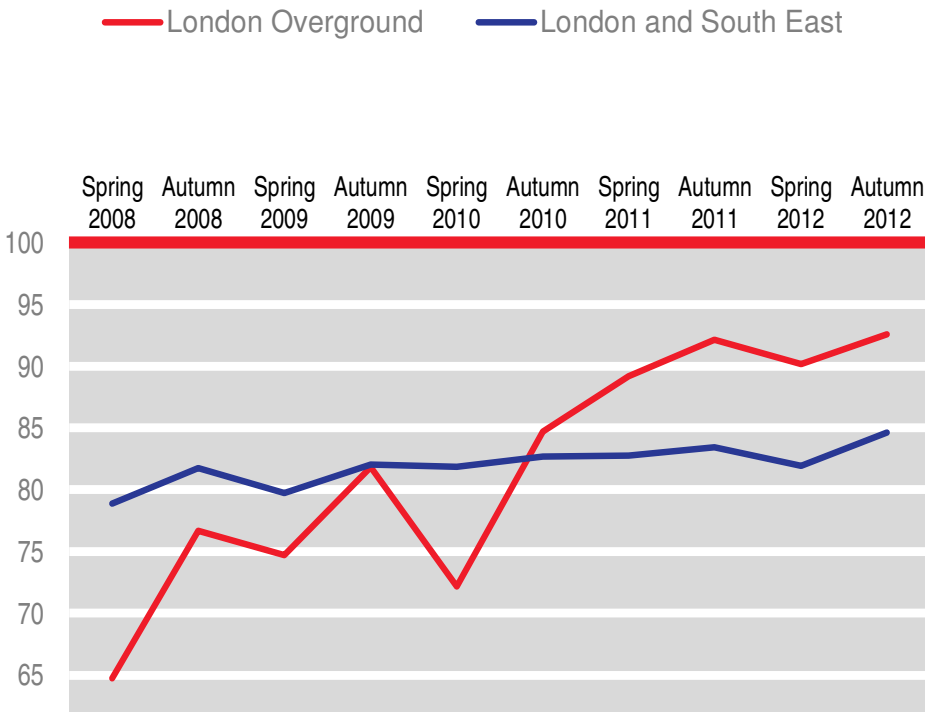


Figure 9: Modes Previously Used By Additional London Overground Passengers<sup>1</sup>

### L. Performance – Customer Satisfaction

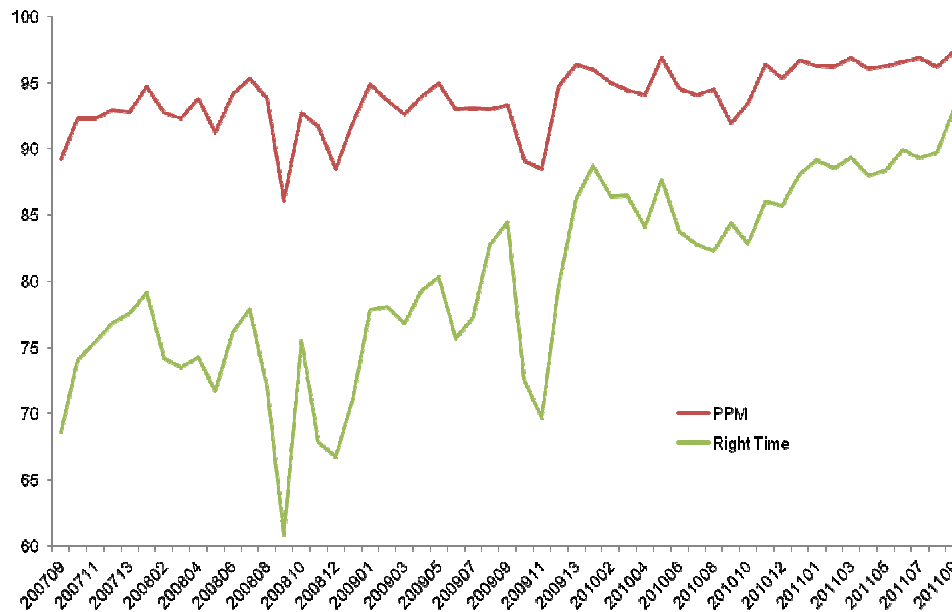
The railway passenger watchdog Passenger Focus undertakes research throughout the year to gauge railway passengers' opinion and raise concerns across the country. Passenger Focus's mission is to get the *best deal for Britain's passengers*<sup>23</sup>. Twice a year Passenger Focus undertakes a National Passenger Survey to produce a report on each of the UK's train operating company's performance. The graph below illustrates how passenger's overall satisfaction levels have increased by nearly a half from 64% to 93%.



**Figure 10: Overall Satisfaction with London Overground between 2008 and 2012 (%)<sup>19</sup>**

### **M.Performance – Punctuality**

Like all UK train operating companies London Overground is given a score on its performance with regard to punctuality of its services. Two measures are used: Public Performance Measure and Right Time. The former indicates which percentage of the services that the train operator runs arrived within five minutes of the train's scheduled arrival time<sup>24</sup>. The Right Time performance measures the percentage of trains arriving early or within 59 seconds of schedule<sup>25</sup>. The graph below indicates London Overground's performance since Transport for London took over the concession in 2007. The latest figures for London Overground are 96.8% on Public Performance Measure and 86.6% on Right Time Measure, both annual moving averages for July 2012 to 2013. These compare to 91.1% and 73%, respectively, when the management of the routes was taken over by Transport for London. As the graph below illustrates, on top of the notable increase in punctuality, the gap between the Public Performance Measure and Right Time measure has been narrowed since the concession was taken over.



**Figure 11: Public Performance Measure & Right Time Performance on London Overground from 2007 to 2011<sup>26</sup>**

### III. Conclusion

London Overground has been a success with regard to various metrics. It has provided a popular complementary service with enhanced capacity along the routes and in turn freeing up capacity on other routes. It has also demonstrated the validity of Transport for London's call to give the Mayor of London, who supervises Transport for London, greater powers over transport in the capital<sup>9</sup>. Not only can this offer customers a better integrated transport provision, but it can also ensure the efficient use of investment and maximise revenues. Transport for London believes that giving the Mayor a budget to operate London's entire rail network would *enable the Mayor to balance London's transport needs and service standards across the capital*<sup>9</sup>. London Overground's success underlines the argument for Transport for London's call.

London Overground is a successful example of the *in-fill* services Transport for London refers to in their *Delivering the Mayor's Transport Strategy*<sup>9</sup> which are intended to complement the major schemes by focusing management and invest in transport provision. London Overground has improved connectivity to the areas it services, the popular service reroutes journeys that previously were via Central London and thereby frees up capacity in the central areas. The strategic interchanges it has creates between radial and orbital services contributes to this. The higher service quality and frequency as offered customers across London better transport provision and greater access to opportunities and services.

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# Travel Journey Appraisal: Communicative Evaluation Of Service Experience

R. J. Clarke<sup>a\*</sup>  
H. K. Brown<sup>b</sup>

**Abstract:** For its users, infrastructure is not an artefact; it is in fact an experience. Understanding a customer's response to a specific transport service involves appraisal resources; communication resources by we express evaluation, attitude and emotion. Customer appraisal responses can be registered to transport systems. This literally enables maps to be created that reveal customer evaluations, attitudes and emotions associated with locations along a transport route. Comparative studies of service experience are possible by conducting appraisal analyses of interviews from different customers segments. This paper identifies the key methodological issues and their resolution to develop a communication oriented spatial normalization procedure that enables appraisal to be visualized for a journey. Using a study of authentic local shuttle services, this paper describes how the 'go along' interviews method can be conducted in order to undertake the appraisal analyses and how travel journey appraisal can be used to map customer service experience along transport routes

**Key words:** Service experience; Communication; Systemic functional linguistics; Appraisal; mapping

## I. Orientation to Travel Journey Appraisal Project

While we cannot think about transport infrastructure without thinking about those who use it and ultimately pay for it, the ways we need to think about transport users' service experiences are completely different to the ways we need to think about the engineering and planning concerns associated with transport infrastructure. In attempting to understand the expectations that users have of available transport services and how they construe these experiences, traditional service marketing or service quality researchers usually employ surveys and questionnaires to quantitatively determine service satisfaction levels. While the post-hoc results of these types of quantitative studies may inform political discourse or public debate, they rarely have relevance for transport users nor can they directly inform infrastructure engineering practices. We describe part of a study called Travel Journey Appraisal (TJA) that has developed

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<sup>a</sup> Collaboration Laboratory (Co-Lab), SMART Infrastructure Facility, University of Wollongong, NSW 2522

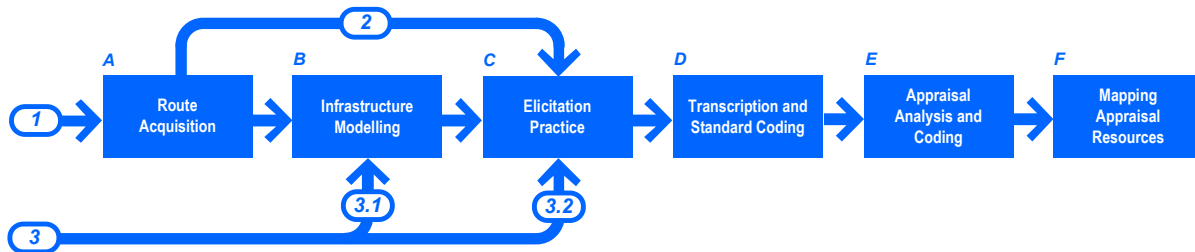
<sup>b</sup>Spatial Analysis Laboratories, Faculty of Science, Medicine and Health, University of Wollongong, NSW 2522

\*Corresponding author: Rodney Clarke [rclarke@uow.edu.au](mailto:rclarke@uow.edu.au)  
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a novel approach for determining and representing transport user experiences, utilising geo-located transcription, Systemic Functional Linguistic (SFL) communication methods for elicitation and analysis, as well as applied spatial science concepts for visualisation. While the way we recover and represent user experience is communicative and qualitative, the analysis deliverables are provided in a form that can be understood by users and directly utilised by designers, builders and maintainers of transport infrastructure. While the TJA methodology and workflow is briefly described (in §2), this paper emphasises the role of appraisal resources that are used to encode evaluations of service experience (in §3) and the modeling and mapping of appraisal resources (in §4). These stages in the TJA methodology will be exemplified using a free city transit bus service operating in Wollongong, NSW Australia.

## II. TJA Stages, Workflow and Methodology

The TJA methodology involves a number of stages: (A) Route Acquisition, (B) Infrastructure Modelling, (C) Interview Elicitation Practice, (D) Transcription and Standard Coding, (E) Appraisal Analysis and Coding and (F) Mapping Appraisal Resources; see Figure 1. There are three workflows that can be usefully formed from these stages. The workflow for a new complete study involves undertaking Stages A through to F inclusively; see Figure 1 (1). The Route Acquisition stage involving the collection and processing of geotraces and points of interest (Figure 1, Stage A), and the Infrastructure Modelling stage involving the construction of metric, virtual 3D infrastructure objects (Figure 1, Stage B) are not considered further here. In ongoing studies these stages would have either been completed or are not required. As a consequence, two additional workflows used for on-going studies drop the Route Acquisition stage, see Figure 1 (3.1), or drop both it and the Infrastructure Modelling stage in Figure 1 (3.2).



**Figure 1. TJA Stages, Workflow and Methodology.**

Ethnographic and ethnomethodological approaches for determining customer expectations and valuations of public transport services are not unusual<sup>1,2</sup>. Typically studies employ go-along interview techniques where the researcher and customer engage in an extended interview throughout the journey<sup>3</sup>. Go-along interviews provide transport researchers with the opportunity to study travellers' perceptions of place (locations, districts and so on) and infrastructure spaces (shelters, interchanges and the like). They also provide opportunities to observe traveller interactions with all aspects of the transport system as experienced: its physical manifestation as engineered artefacts, the functional organisation of its social groups, the signage and other informational elements that constitute soft infrastructure as well as the range of services and the manner of their provision by the transport system. In the TJA study, go-along interviews are recorded using wearable, portable digital video cameras. Their high definition removes the need for using mechanical camera stabilisation systems in the field. Undesirable camera movement

can be removed as a data preparation phase. Smoothing video allows customer movements, gestures, and facial expressions to be clearly seen and coding if required. The wide angle lens allows views out of the bus windows and so provides a degree of locational ‘ground truth’ along the route. A given journey is recorded in ‘one take’ without edits in order to preserve the time-code. The time-code information also enables segment timings and the total journey time to be calculated and approximate location at any given time to be determined. This provides a useful backup for the small GPS unit carried by the researcher.

In traditional studies of travel experience, a think aloud protocol is often preferred as a ‘naturalistic method’ whereby the traveller volunteers information without any direction or prompting from the researcher<sup>4</sup>. The quality of the resulting transcript is dependent on the traveller’s interest and ability to self-elicite information about the transport system during the journey. In fact using this protocol often meant that the length and quality of the transcripts was poor; travellers would simply stop talking assuming that they had nothing further to contribute<sup>5</sup>. From a communication perspective, the linguistic resources of self-elicited texts are substantially different from others. At least in travel service experience studies, the use of think-aloud protocols is not ‘naturalistic’. In order to improve the duration and quality of the interactions between travellers and researchers, an elicitation practice (Figure 1, Stage C) was developed using SFLs conventional communication pattern resources (canonical genres) that we all learn as members of our respective cultures. This elicitation practice had been previously developed for use in systems development interviews<sup>6</sup>.

The go-along interview is transcribed and coded using video transcription system called Transana developed at the University of Wisconsin, forming a geocoded transcript (at Figure 1, Stage D). These transcripts can be imported into Atlas ti to provide powerful qualitative and descriptive statistical options if required. Transcripts can be coded in any number of ways. For the TJA study, the most important kind of coding involves appraisal resources (described in the next section). Stages E and F are emphasised in the remainder of the paper.

### **III. Appraisal Resources**

One area that has been intensively studied in the service disciplines is the emotional content associated with services. In the services marketing literature, emotion or affect is considered to be an important aspect of the traveller’s assessment of the service experience. However from a SFL perspective, affect is only one of four interrelated communication resources collectively referred to as appraisal. While it is recognised that qualitative and ethnographic approaches have the potential to access the customer’s experience of transport systems and their associated services, little is understood about the language resources that stakeholders and researchers actually employ when characterising and representing experience. If we want to understand a customer’s response to specific transport services then appraisal resources are particularly relevant. Appraisal resources include those communication resources by which we “express, negotiate and naturalise particular inter-subjective and ... ideological positions ... [involving] the language of evaluation, attitude and emotion”<sup>7</sup>. The earliest formulation of the Appraisal system was after Martin in educational applications<sup>8</sup> and this formulation was subsequently adopted by Eggins and Slade in their attempts to interpret casual conversation from a systemic perspective<sup>9</sup>. This formulation of the Appraisal system consists of four communication

resources, those associated with judging, evaluation, emotion and amplification, defined in Table 1.

A customer who suffers from a disability like diabetes may suffer from stability issues and as a consequence may react negatively to jerky and abrupt motion in the bus (-r) while simultaneously expressing dissatisfaction (-d) and evaluating both the particular driver and their employer negatively (-s). A young mother with a stroller and a toddler may express happiness (+u) for assistance onto a bus and judge positively the driver, their employer and those passengers who also provided aid (+e). Various combinations of appraisal resources are possible simultaneously throughout the journey. These examples might be very useful to improve driver training or indeed identify systematic issues with the elements of the bus and the bus stop that make it difficult to manoeuvre a stroller from a path onto the bus.

**Table 1. Appraisal Resources with associated probes in italics<sup>8,9</sup>. Resource codes are bracketed. Square brackets indicate lexical and/or grammatical units with +/- indicating their presence/absence. Types of ranges ( $\pm n$  or  $0 \rightarrow n$ ) for appraisal visualisation are described in the text.**

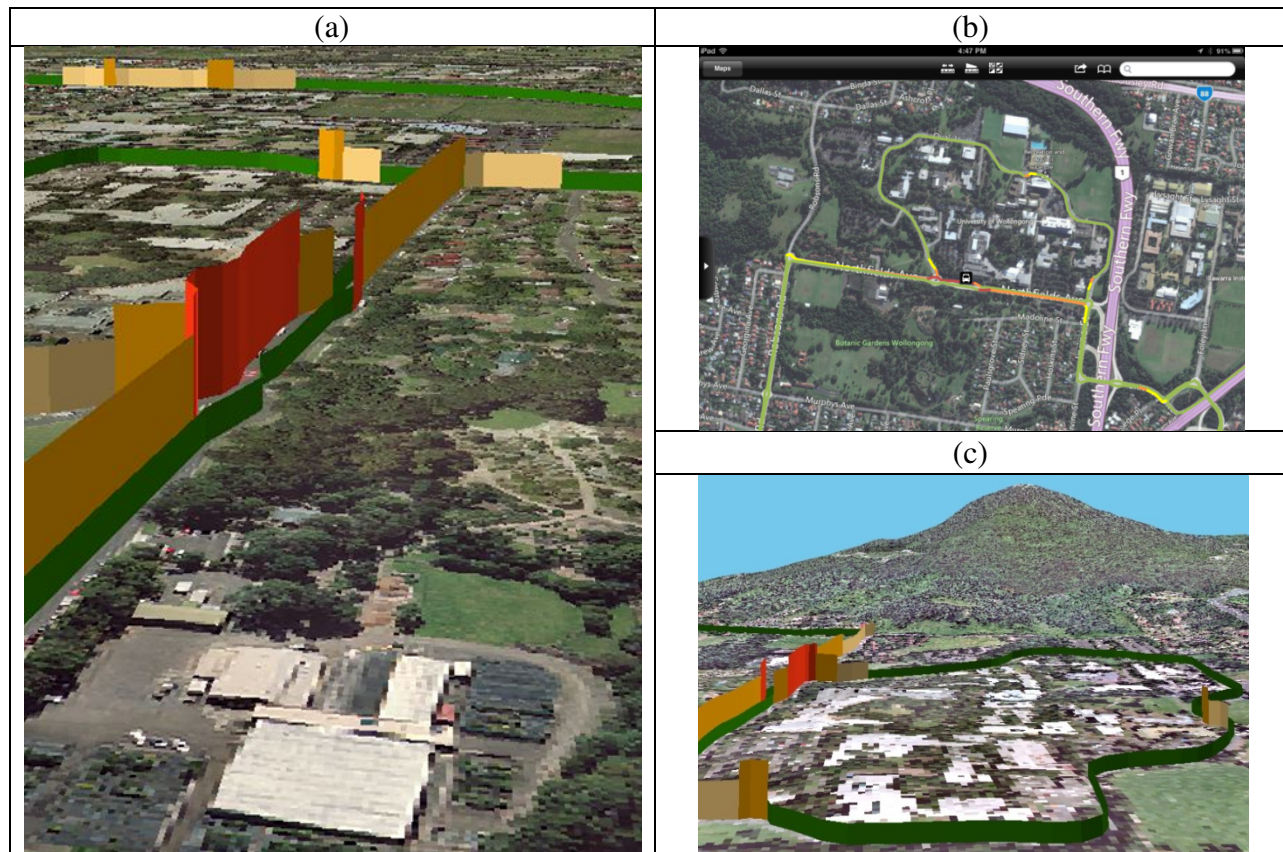
<b>Appreciation (P)</b> reactions to and evaluation of reality, objects or processes <i>What do you think of it?</i> [lexis (adjectives), clause grammar]		
<b>Reaction (r)</b> expression of emotional states both positive and negative	<i>What did/do you think of it?</i>	$\pm n$
<b>Composition (c)</b> how harmoniousness is a social process or text	<i>How did/does it go together?</i>	$\pm n$
<b>Valuation (v)</b> evaluations of the content or message being expressed.	<i>How did/do you judge it?</i>	$\pm n$
<b>Affect (F)</b> expressing feelings and emotions <i>How do you feel about it?</i> [lexis, + contrastive pairs]		
<b>Un/happiness (u)</b> encoding happiness or sadness in language	<i>How happy did/do you feel?</i>	$\pm n$
<b>In/security (i)</b> encoding anxiety or confidence in language	<i>How secure did/do you feel?</i>	$\pm n$
<b>Dis/satisfaction (d)</b> increase or degree of intensity being communicated.	<i>How satisfied did/do you feel?</i>	$\pm n$
<b>Judgement (J)</b> evaluations of the people's ethics, morality or social values <i>How do you judge this?</i> [lexis, clause grammar]		
<b>Social sanction (s)</b> reactions to and evaluation of reality	<i>How moral? How believable?</i>	$\pm n$
<b>Social esteem (e)</b> expression of emotional states both positive and negative	<i>How strongly committed? How usual/destined? How able?</i>	$\pm n$
<b>Amplification (M)</b> grading attitudes towards people, places, things or events <i>How to grade attitudes along a continuum?</i> [lexis - contrastive pairs]		
<b>Enrichment (n)</b> reactions to and evaluation of reality	<i>Attitudinal colouring added when and otherwise neutral word has been used?</i>	$0 \rightarrow n$

<b>Augmenting</b> (a) expression of emotional states both positive and negative	<i>Amplifying or intensification of attitudinal meaning?</i>	$\pm n$
<b>Mitigation</b> (m) evaluation of the ethics, morality or social values of others	<i>Mitigate or play down attitudinal meaning?</i>	$\pm n$

#### IV. Appraisal Modelling and Mapping

Customer appraisal resource values can be registered to transport systems; literally enabling maps to be created that reveal customer evaluations, attitudes and emotions associated with locations along a transport route, see Figure 2. To be able to map appraisal along the transport route a number of methodological breakthroughs were required. These involved data collection and elicitation strategy described in §2 and also how experience is encoded using Appraisal resources. One methodological problem involved determining how fine grained the spatial scale could be if communication techniques. This led to the development of communication-oriented spatial normalisation procedures that enabled appraisal to be determined at specific points along the route. Any given transport route is broken up into a number of functional segments based on the route topology, the environment along the route (the arrangement of the stops, stations, transfers stations and terminals) and the service requirements of the transport system as a whole. Segments provide a means to geo-locate appraisal resources throughout and across transport networks and provide the means to compare transport experiences between successive travelers. The user's experience is the route! Transcripts are coded for appraisal resources and the completed appraisal analysis is mapped to the segments. Each of these appraisal resources can be considered as its own intensity scale (see right hand column in Table 1 and individually visualised as shown in Figure 2. In these images, the 'ribbons' aligned to the roadways have been extruded based on ordinal intensity-based chloropleth classification. The same attribute determines the colour and the height of the ribbon at any given segment. Appraisal resources are organised using either a positive scale (0→n) or a positive/negative scale ( $\pm n$ ) in Table 1. Figure 2a shows an example of the appraisal resource- enrichment (red). Those paths that provide no evidence for enrichment are presented as green.

Individual service experiences can be visualized using a GIS system as can aggregate data from multiple interviews (Figure 2a). Comparative service experience studies from different travel groups can also be visualised. Visualisations can be tailored to different stakeholders and interest groups. Figure 2b shows appraisal results along one route of the free Wollongong city transit bus service as a 2D Appraisal map in ESRI ArcGIS for the iPad. Another visualisation involves a draped Appraisal extrusion over a digital elevation model in 2½D. This would be useful for strategic decision makers and transport analysts.



**Figure 2. Mapping Appraisal Resources: (a) aggregated Enrichment from multiple journeys, (b) 2D Appraisal Map in ESRI ArcGIS for iPad, and (c) Draped Appraisal Extrusion over a Digital Elevation Model in 2½D using ESRI ArcScene.**

## V. Conclusions and Further Research

To the best of our knowledge the geo-location and mapping of discrete user experiences of transport systems has never previously been undertaken. Perhaps this is because standard approaches to researching transport experiences had to be abandoned. The TJA study required the development of several novel communication methods, particularly the application of a theorised communication strategy to eliciting responses from travelers during go-along interviews as well as the application of appraisal methods to the resulting geo-located transcripts. A GIS was used to visualise each appraisal resource as a ribbon-like ordinal intensity-based choropleth classification aligned to the transport route. Different visualisations suitable for travellers, transport engineers and planners are possible with this technology. The efficient application of these methods for the general public suggests a new form of Public Participation GIS (PPGIS) and more broadly a new communication-based form of travel service experience study.



With a sufficiently trained field researcher and an appropriate app, it would be possible to code appraisal resources as they occurred in real-time. This would mean it would be possible to have provisional appraisal maps developed on-the-fly as the research was being undertaken in the field without necessarily going through a lengthy transcription process. Because SFL is a comprehensive and complete model of language, the TJA methodology could be generalised to create many different kinds of travel communication studies. This would require the replacement of Stage E with an SFL method selection procedure. Stage F would also need to be generalised in order to visualise arbitrary combinations of communication resources.

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# Estimating the Emission Reduction Potential of Australian Transport

David Cosgrove<sup>a</sup>  
David Gargett<sup>a</sup>  
Caroline Evans<sup>b</sup>  
Paul Graham<sup>c</sup>

**Abstract:** The Australian Low Carbon Transport Forum (ALCTF) – initiated by ARRB Group, BITRE and CSIRO – was organised to gather knowledge on possible options for transport emission abatement, with the participation of a diverse range of government, industry, academic and other research organisations. The ALCTF aimed: to generate a list of options with the potential to significantly improve the efficiency of the Australian transport sector; identify the possible magnitude of greenhouse gas emission reductions for each option, both individually and when combined; examine challenges to achieving the options' full potential and investigate any uncertainties, especially concerning their likely effectiveness. This interdisciplinary study analysed a wide range of emission abatement prospects, covering vehicle and fuel technologies, infrastructure improvements and land-use planning, travel demand management, mode shifts and other behavioural change. A novel aggregation process was developed, to estimate the maximal potential reduction, by 2050, from a full package of measures acting together – with the results demonstrating that large reductions in currently projected greenhouse gas emission levels should be technically feasible, even with increasing population, without sacrificing access to transport services.

**Key words:** Emission projections; Technology assessment; Infrastructure improvement; Transport demand management

## I. Introduction

The Australian Low Carbon Transport Forum (ALCTF) was organised (by a project secretariat comprising ARRB Group, BITRE and CSIRO) in an effort to bring together knowledge on greenhouse gas abatement options for Australian transport, and explore just how deeply future emissions could plausibly be cut across the sector. With the participation of around thirty organisations (ranging across government, industry, academic and other research agencies), a set of emission abatement prospects were evaluated, covering the areas of vehicle and fuel technology, infrastructure improvements, travel demand management, modal shifts and

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<sup>a</sup> Bureau of Infrastructure, Transport and Regional Economics (BITRE), Canberra ACT 2601

<sup>b</sup> ARRB Group, Vermont South VIC 3133

<sup>c</sup> Commonwealth Scientific and Industrial Research Organisation (CSIRO), Newcastle, NSW 2300  
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various other behavioural or urban design changes. This paper, which outlines the ALCTF process, and the methodologies used to analyse the feasibility of the different options, essentially summarises parts of a detailed report on the project's main results, Greenhouse gas abatement potential of the Australian transport sector: Technical Report<sup>1</sup>.

Basically, the aims of the ALCTF were to generate a comprehensive list of possible options for reducing greenhouse gas emissions from the Australian transport sector; and to identify how significant potential emission reductions could be both for each option acting individually and when combined as an aggregate set of measures. The ALCTF process also strove to examine any obstacles or challenges to achieving the options' full potential, and to investigate any uncertainties or knowledge gaps, especially concerning the options' likely effectiveness, timing or practicality.

## **II. Workshop Overview**

The core of the ALCTF process consisted of a series of workshops, with a diverse range of forum participants contributing a wide variety of expert knowledge on possible abatement opportunities. Between July and November 2011, three workshops (one each in Melbourne, Sydney and Brisbane) were conducted. An extensive list of possible abatement options resulted from the workshop discussions, which were then prioritised by the ALCTF participants, selecting a set of measures for analysis (shown in Figure 1) that attempts to cover a reasonable sample of the abatement opportunities likely to be available within the transport sector over the coming decades. The list of options given in Figure 1 is not intended to be exhaustive or prescriptive (that is, it does not claim to contain every single emission abatement measure worthy of consideration), but aims to be roughly representative of the maximal abatement that could potentially be achieved by about 2050 (while roughly maintaining current levels of transport amenity or utility) from an integrated package of transport sector options acting together. Note that 'maximal' here means the amount of emission reductions (relative to currently expected trends) judged (through discussions of the participating organisations) to be approaching the limits of social and economic constraints but remaining technically feasible.

Implementing such a full package of options would entail a range of behavioural and technological changes, both for the transport sector and across the wider Australian community. For example, this may involve policies encouraging: urban road pricing or other congestion management technologies, the control of grossly polluting vehicles, enhanced vehicle fuel efficiency or the accelerated uptake of some technology prospects (such as electric vehicles or second-generation biofuels, for which eventual fleet penetration will partially depend on the resulting future trends in fuel, vehicle and infrastructure prices ); and even some longer-term lifestyle changes (such as could result from workplaces allowing greater use of telecommuting or the greater adoption of walking or cycling following urban re-design).

The latter part of the Workshop process concentrated on investigating how the selected greenhouse gas abatement options might interact when combined, and thus the ALCTF analyses examine the options both individually (as stand-alone alternatives) and as part of an aggregate package of measures (under an 'Aggregate Scenario' aimed at modelling the maximum abatement technically feasible by 2050 from the chosen options all acting together, allowing as

much as possible for their likely overlaps or interactions). Workshop participants were also asked to consider likely co-benefits and disbenefits for each option, and to provide their views on how much of a challenge possible social or economic constraints might pose to the successful adoption of the various abatement options.

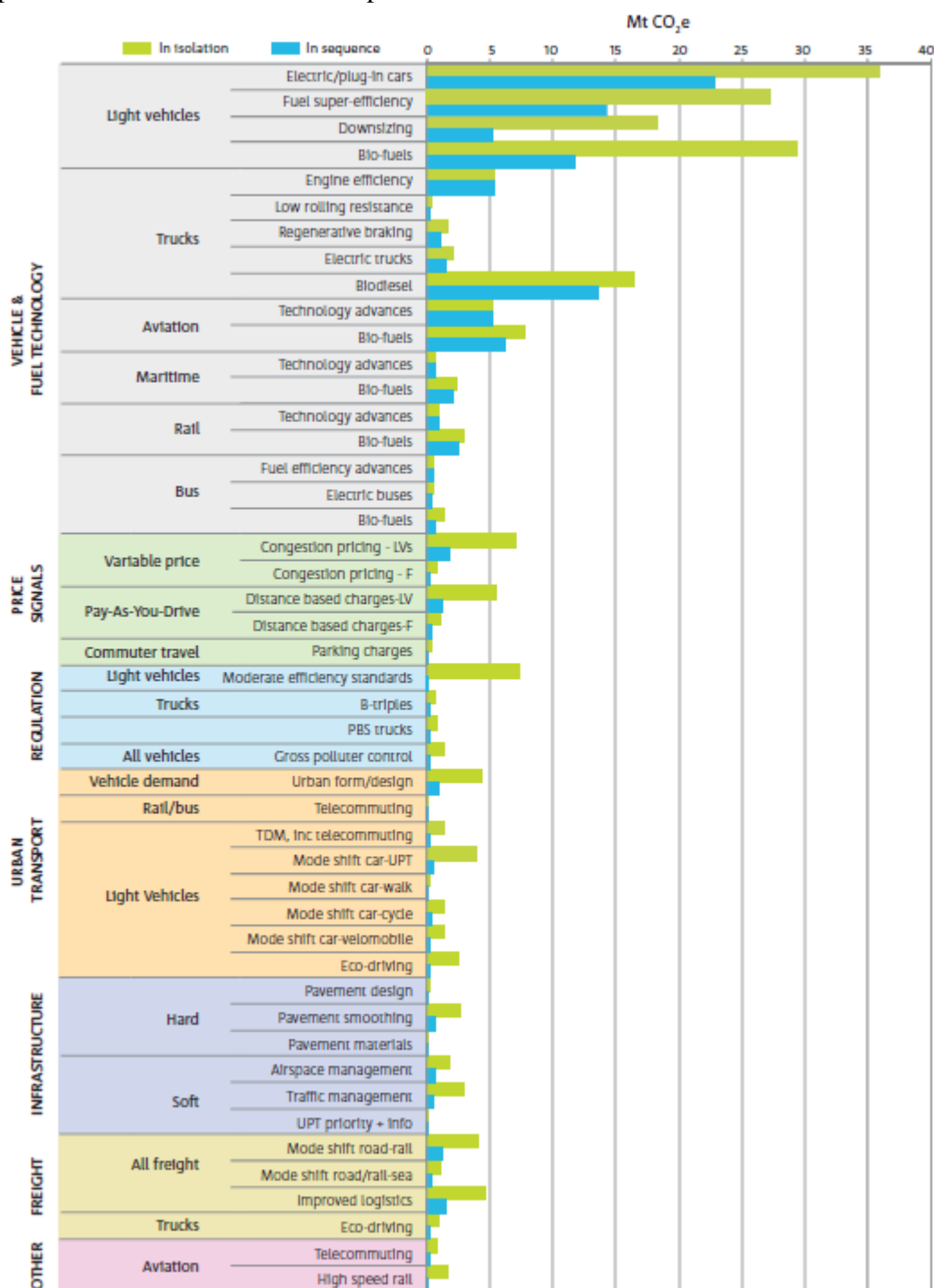


Figure 1. Estimated maximum per annum greenhouse gas reduction that could be achieved by selected transport abatement options, considered in isolation and as an in sequence contribution to a transport sector aggregate, by 2050.

Notes: LV – light vehicle, F – freight vehicle.

‘In sequence’ values strongly depend on the evaluation order chosen for the option aggregation, and are not necessarily representative of actual individual effects or technical potentials.

Sources: Cosgrove et al<sup>1</sup>, CSIRO<sup>2</sup>.

### III. Abatement Estimation

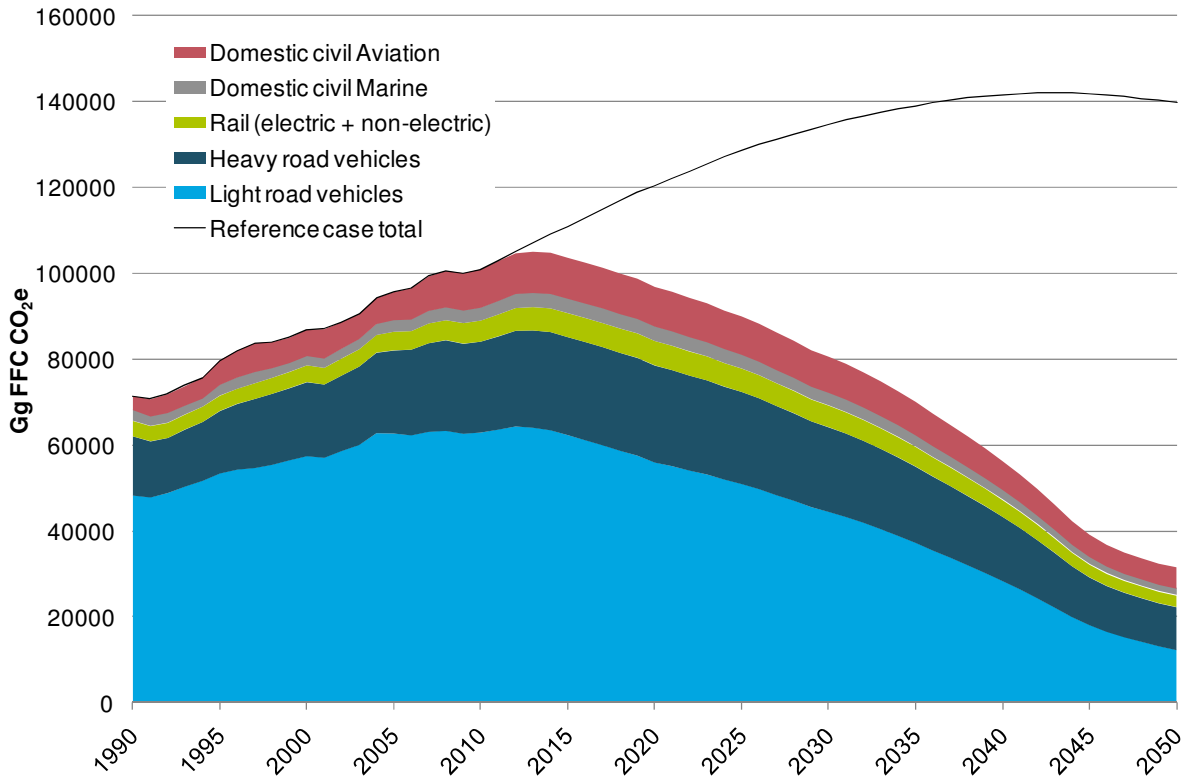
Essentially, the amount of abatement an option might achieve is dependent on 1) its level of eventual adoption in a given segment of the transport sector, 2) the greenhouse gas emissions expected in that market segment and 3) how effective the measure is in reducing emissions relative to conventional operating conditions. The ALCTF assessed each of these basic elements, across the set of chosen options.

A calculation of expected abatement has to be made relative to some projection of likely future conditions, usually referred to as a *reference* or *base* case. Since the abatement estimates are here calculated in relation to projections of 2050 transport emissions (under a ‘base case scenario’), rather than current levels, the particular specification of that reference scenario has a significant bearing on the resulting calculations. For example, any technological prospect assumed to achieve substantial future market share even under business-as-usual trends may have only a slight 2050 abatement potential estimated for any extra market penetration (relative to the reference case) even if offering large efficiency gains relative to *current* practices. The reference scenario adopted for the ALCTF assessments used base case transport projections developed by BITRE<sup>3</sup>; based on current trends in major economic indicators and demography, with continuing growth in national population (reaching about 36 million persons by 2050) and average income levels (see Treasury<sup>4,5</sup>), but only gradually increasing oil prices (using IEA<sup>6</sup>).

Road vehicle use per person is expected to exhibit a slight upward trend to 2020, as residual damping effects after the Global Financial Crisis gradually wear off. However past 2020, road vehicle kilometres per person will tend to saturate if currently identified structural trends<sup>7</sup> continue to hold; and daily travel levels in Australia are likely to increase more slowly in the future than for the long-term historical trend. However, the business-as-usual projections have continuing strong growth in domestic air travel and freight movement (both averaging growth of over 2 per cent per annum over the forecast period 2010-2050). Under the reference scenario assumptions, expected innovation in vehicle and engine technology, leading to gradual improvements in average fuel efficiency, serve to roughly stabilise aggregate end-use energy consumption by Australian domestic transport from about 2040 on (see Figure 2).

Since many of the options being assessed by the ALCTF involve possible changes to fuel supply, solely *end-use* emission values are not fully suitable for such analyses. For a more complete picture of total emissions output due to Australian transport (especially since end-use values do not include any of the emissions due to electricity use), estimates of full fuel cycle (FFC) emissions are derived for these evaluations. ‘Full fuel cycle’ values refer to the inclusion of emissions released during transport fuel supply and processing (including from petroleum refining or biofuel production), and during power generation (for electric vehicles or railways), as well as from direct fuel combustion. This means that when any alternative fuels are considered, all emissions associated with their supply are taken into account, which is important

since some fuels have considerable upstream emissions, but very low or zero emissions during their use. For example, carbon dioxide emissions from the use of biofuels are traditionally assigned a zero level for emission inventory accounting purposes, assuming that the amount of carbon dioxide from their direct combustion will be reabsorbed when the biofuel feedstock is regrown. However, with FFC evaluations, emissions associated with cultivating, harvesting, transporting, processing and converting the feedstock biomass into biofuel are also accounted for, providing the estimates of *net* emissions from biofuel consumption used in this study.



**Figure 2. Maximum potential abatement projected for Australian transport sector, ALCTF Aggregate Scenario compared to Base Case projections.**

**Notes:** CO<sub>2</sub> equivalent emission values here include only contributions of direct greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O). Full fuel cycle (FFC) estimates include emissions due to energy supply and conversion, as well as from fuel combustion. Net emissions for biofuels are also estimated here. ‘*Aviation*’ is all civil domestic aviation (i.e. including general aviation, but excluding military aircraft). ‘*Marine*’ consists of emissions from coastal shipping (including any fuel consumed by international vessels undertaking a domestic freight task), ferries and small pleasure craft (and excludes fuel use by military and fishing vessels). ‘*Light Road Vehicles*’ include all passenger cars and Sports Utility Vans, Light Commercial Vehicles and motorcycles. ‘*Heavy road vehicles*’ include all trucks (rigid and articulated) and buses.

**Sources:** BITRE estimates, BITRE<sup>3</sup>, Cosgrove et al<sup>1</sup>.

The upstream emission intensities of various fuels are unlikely to remain constant, with some expected to improve considerably over time. For example, it is assumed in these assessments that Australian electricity generation becomes increasingly less carbon intensive, and that biofuels

become progressively sourced more from non-food feedstocks typically requiring less resources to produce (such as fertiliser, conversion energy or necessary land area). Specifically, the FFC values derived for the ALCTF assume that the provision of electricity decarbonises over time consistent with Treasury modelling. In the Treasury ‘core policy scenario’<sup>8</sup>, generation emission intensity (in tonnes of CO<sub>2</sub> per megawatt-hour of electricity delivered) is forecast to reduce by about 30 per cent over the next 20 years, and by around 75 per cent by 2050. Such a reduction in emission intensity significantly improves the appeal of electric vehicles as a transport abatement option.

In accordance with current National Greenhouse Gas Inventory specifications for reporting of carbon dioxide equivalent (CO<sub>2</sub>e) quantities<sup>9</sup> (DCCEE 2010), the values herein include only the effects of the *directly* radiative gases emitted from transport fuel combustion, comprising carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Aggregate emission volumes for the reference case in 2050, at approximately 140 thousand gigagrams of direct CO<sub>2</sub>e (where Gg = 10<sup>9</sup> grams, equivalent to thousand tonnes), are approximately 38 per cent higher than 2010 levels for domestic transport (see upper line in Figure 2).

The green bars in Figure 1 give the results derived for the individual impact of each option ‘in isolation’ (that is, the emission reduction for that option if all else stayed the same as the reference case) – presented separately for each of the 47 abatement possibilities selected for ALCTF assessment – demonstrating the significant potential of enhancements to vehicle and fuel technologies. Though this allows us to see each option’s *discrete* potential, adding up these ‘in isolation’ values does not give an appropriate *cumulative* total, for the possible action of the whole set of options (since such a tally does not adequately account for their overlapping effects). The estimation method for the Aggregate Scenario thus entailed setting an order, for calculating the successive steps of each option’s contribution to a summed total; with the sequencing, also given in Figure 1 (options summed from the top of the chart down), being agreed amongst workshop participants as a reasonable evaluation order. The particular order chosen has no objective meaning, and changing this sequence would not alter the final estimate for aggregate abatement, just the individual steps during its computation. That is, if an option were to be moved down the evaluation list, its resulting ‘in sequence’ abatement value would tend to reduce (since the *residual market* – or remaining emissions – upon which it now acts, resulting from the actions of all the options higher in the Figure 1 listing, would be correspondingly reduced). Likewise, any options moved up the list would tend to have their ‘in sequence’ values increase accordingly.

Summing across the ‘in sequence’ contributions (given by the blue bars in Figure 1) to the ALCTF Aggregate Scenario yields a total sectoral abatement estimate of about 108 thousand gigagrams of direct CO<sub>2</sub>e per annum by 2050 (relative to the business-as-usual assumptions). This corresponds to the abatement potential of all the options acting together being equivalent to a roughly 77 per cent reduction in the (reference scenario) projected level of transport sector emissions (Figure 2). The divergence between the Base Case trend for total FFC greenhouse gas emissions, from Australian civil domestic transport, and levels that could potentially hold – following implementation of a full package of options such as that comprising the ALCTF Aggregate Scenario – widens over time (as displayed in Figure 2, which also shows the estimated modal composition resulting from the set of options’ collective activity). That is, under

such combined and concerted action, transport emissions are projected to fall to around 32 thousand gigagrams CO<sub>2</sub>e per annum by 2050.

This particular abatement assessment assumes that a large proportion of Australian vehicles would be capable of running on biofuels/biofuel blends by 2050, with such fuel use assumed due to bio-derived ethanol and biodiesel from a range of currently available sources (1<sup>st</sup> generation biofuels) and projected future feedstock materials (2<sup>nd</sup> generation biofuels). Note that the various biofuel options have some of the greater uncertainty levels associated with their abatement evaluations, since there is considerable on-going debate concerning issues such as: possible land use conflicts with food production; exactly how much biofuel volume can be produced sustainably; and how efficient various prototype biofuel production technologies will actually be when operating at large scale<sup>d</sup>

## I. Conclusions

Based on extensive input from transport experts, a representative set of 47 individual abatement options for the transport sector were examined in detail, and had their maximal potential for future emission reductions assessed. These included a large number of fuel and vehicle technologies (especially concerning vehicle electrification and biofuel use), urban transport measures, new and alternative infrastructure, and options to modify behaviour via regulation and price signals. The large number of available options identified by the forum testifies to how complex and diverse the transport sector is. The ALCTF process has demonstrated that it should be technically feasible for Australian domestic transport to have its aggregate sectoral emissions decline over time, under the action of an integrated package of measures, to be around 64 per cent lower than year 2000 levels by 2050 (Figure 2), without severely compromising overall transport utility. This reduction could be obtained using a range of technologies either currently available or likely to be commercialised in the near to medium term (assuming certain research or infrastructure developments progress sufficiently over the coming decades, such as decarbonisation of the electricity grid or the adequate availability of affordable 2<sup>nd</sup> generation biofuels derived from environmentally sustainable feedstocks), and a variety of standard transport demand management options (such as congestion pricing, improvements to freight logistics or mode changes).

The ALCTF scenarios were assessed primarily independent of explicit cost considerations. However, even though the study did not seek precise quantification of the costs of individual options, it appears that incremental investment in the order of \$A5-10 billion per annum (whether public or private, with the major cost components, across the set of options identified

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<sup>d</sup>That is, the estimated level of possible abatement is predicated on there being an adequate supply of affordable second-generation biofuels in the future. This will be subject to technological development outcomes and to competing needs for biomass possibly limiting transport sector availability. Based on CSIRO assessments of likely future availability of domestic biofuels (such as Farine et al<sup>10</sup>), the ALCTF scenarios place limits on total biofuel use, where it is assumed that annual abatement greater than about 15-20 million tonnes (Mt) CO<sub>2</sub>e per annum for biodiesel and about 30-35 Mt CO<sub>2</sub>e per annum for ethanol would probably suffer biofuel supply constraints (after allowing for likely *sustainable* Australian feedstock capacities and roughly equivalent extra volumes from imports).



here, probably relating to the provision of extra vehicle technology) could be required to implement such a package of abatement measures. Over time, this investment will generally deliver financial benefits, primarily in the form of fuel savings, which are expected to eventually more than offset the incremental costs (that is, deliver net social benefits over the longer term, with the up-front costs more than balanced by advantages such as reduced fuel consumption, traffic congestion improvements or health benefits from better urban air quality).

The aggregation process conducted here is quite approximate in nature, and there are significant uncertainties surrounding many of the abatement assessments, yet such a collective set of options should certainly offer substantial emission reduction potential, as long as any social or economic obstacles to their implementation can be successfully overcome. For example, ongoing global research, development and industrial deployment are likely to be required to reduce the costs of some options (where high cost levels will serve to delay or slow their adoption). Any future rises in oil prices will tend to act as a significant incentive, accelerating the take-up of some options. It is possible, however, that a combination of rising fossil fuel prices together with government policies complementing their adoption (by addressing particular social or regulatory constraints affecting various options' acceptance) will be required in order to realise the transport sector abatement potentials identified here by the ALCTF.

### Abbreviations

ALCTF	Australian Low Carbon Transport Forum
BITRE	Bureau of Infrastructure, Transport and Regional Economics
CO <sub>2</sub> e	Carbon dioxide equivalent
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEE	Department of Climate Change and Energy Efficiency
FFC	full fuel cycle
Gg	gigagrams, 10 <sup>9</sup> grams
IEA	International Energy Agency
Mt	megatonnes, 10 <sup>6</sup> tonnes
PBS	Performance Based Standards
TDM	transport demand management
UPT	urban public transport

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# The Planning and Funding of Road Infrastructure via PPPs

John Gardiner<sup>a</sup>

**Abstract:** The shortfall in the funding for construction, operation and maintenance of road infrastructure in Australia is substantial and future investment appears to be beyond the capabilities of government funding alone. In the past, the private sector has proven very willing to invest in PPPs with government to provide road infrastructure and, overall, its performance in relation to construction, operation and maintenance has been far superior to that of government and has relieved government of substantial risk. However, it is unlikely that the private sector will accept the same levels of risk on new PPPs as in the past.

**Key words:** Roads; Infrastructure; Contract procurement; Public Private Partnerships.

## I. Introduction

The shortfall in the funding for construction, operation and maintenance of road infrastructure in Australia is substantial and future investment appears to be beyond the capabilities of government funding alone. In the past, the private sector has proven very willing to invest in Public Private Partnerships (PPPs) with government for the provision of road infrastructure and, overall, its performance in relation to construction, operation and maintenance has been superior to that of government and has relieved government of substantial risk. However, it is likely that the private sector will not accept the same levels of risk on greenfield PPPs as they have in the past. This paper:

- provides a picture of past performance and risk management of Australian road PPPs;
- investigates barriers that exist for efficient future procurement (including the allocation of risk);
- attempts to look afresh at the purpose of urban and inter-urban motorways and congestion and questions whether patchwork tolling exacerbates the problem; and
- considers a number of PPP models and makes some recommendations relevant to future procurement.

## II. Historical Summary

In the early days of road construction in Australia, tollroads, toll ferries and toll bridges were the norm, largely funded by private enterprise. This changed completely during the last century

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, 2522 NSW, Australia  
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with the rise of the State-owned road agencies who eventually took control of almost all road transport. Roads, bridges and ferries became regarded by the public as “free”, which really meant paid for out of taxes.

The 1970’s saw governments becoming aware that the growing demand for road funding was competing with other government priorities (in particular, health and education) and, at the same time, the growth of cities was placing greater pressure on road systems. This led to the introduction of user-funded PPPs, starting with the Sydney Harbour Tunnel, followed closely by the M4 Motorway and the M5 South West Motorway, all in NSW.

Whilst the PPP model used for these and later tollroads has changed over the years, the central premise that a PPP concession must “stand alone” financially has not. All PPPs which rely on tolls are based on a financial model which sets the toll to generate revenue sufficient to fund the project, sometimes in combination with a contribution from the State. User-funded PPPs also move the capital expenditure for the asset off the State’s balance sheet.

The State Agencies of last century set aside large corridors for road development. Most of these have now been utilised. In addition, community concerns related to noise, urban amenity and pollution have seen many roads (even where there is a corridor available) being diverted underground. Consequently, the cost of construction of new motorways has increased considerably. Tunnels can cost as much as ten times their surface road equivalent, further stretching government’s budgets and making it more and more difficult to fund PPP road projects on a “stand alone” basis.

At the same time, there have been a number of financial failures of road PPPs, resulting in considerable losses to the original investors, but not to the State. As a result, most private sector financiers and constructors have now become very reticent to invest in greenfield PPPs where they are expected to accept patronage risk. Furthermore, conservative investors such as superannuation funds find it difficult to commit to investments involving patronage risk. With governments short of cash and reticent to borrow, this has led to a search for alternative PPP models which lessen or remove the requirement for the private sector to accept patronage risk.

### **III. What does the State want from a PPP?**

The State is responsible for network planning. These days, when the State has approached the private sector to build and operate a PPP road project, it has been seeking the following from the successful bidder:

- To “infill” a gap in the planned motorway network;
- To effectively manage its own affairs, including all the following;
- To fund the project, either in its entirety or with a government contribution;
- To design the project, working in collaboration with government guidelines, reference designs and legislation, but usually seeking innovative solutions;
- To construct the project in accordance with the approved design;

- To maintain the road corridor, including pavement, landscaping, fences, signage, tolling equipment, control centre and all roadside communications, controls and messaging;
- To operate the road, including manning the control centre, managing access, controlling traffic speed, congestion (to the extent possible), incident response, network cooperation, attending incidents and cooperation with emergency services;
- To operate a tolling system which enables customers to use their vehicles on the project road and all other Australian tollroads, including building good relationships with customers and providing effective service;
- To demonstrate that the PPP entity is a good corporate citizen; and
- To be an effective issues manager and to minimise the negative impacts to the State of issues arising from the PPP concession.

More recently, some States, acknowledging the longevity of the relationships between the PPP entity and the State, have been seeking mechanisms to address:

- Future expansion and development of the asset;
- Quality of service through the introduction of Key Performance Indicators (KPIs) along with financial penalties for non-performance.

In addition to tollroads operated by the State (State Full Responsibility), there are two broad categories which the State has used for PPPs. These are Full Concession and Hybrids.

#### ***Full Concession***

A private sector consortium is responsible for finance, design, construct, operate and maintain under a concession agreement. The consortium manages customers, tolls the facility and accepts all patronage risk. Some concessions subcontract their customer service activities to others, but remain responsible for them. Later concessions usually have an upside toll revenue sharing arrangement with the State and some have KPIs with penalties for under-performance. Concession periods can vary between 20 and 99 years, but most have been around 30 to 50 years. Some earlier concessions could escalate tolls in excess of CPI, but later ones are limited to increases not exceeding CPI.

#### ***Hybrids***

These lie somewhere between State Full Responsibility and Full Concession, as noted in Table 1 and have taken a number of forms.

#### ***“Right to toll” concession***

A hybrid where the State (or, in Queensland, Brisbane City Council (BCC)) initially undertakes the financing, design and construction, operation and maintenance (and sometimes, tolling), but once patronage ramp-up is complete, tenders a concession for the operation and maintenance with the right to charge customers a toll. Concession periods are generally much shorter because they do not need to amortise the cost of the initial capital works which is borne by the State. There may be risk and benefit sharing with the State in the form of a “cap and collar” to toll revenue.

### *Availability model*

This model is similar to PPPs used for social infrastructure. The private sector concessionaire funds, designs and constructs, operates and maintains for an agreed concession period. The road is free to customers. The concessionaire receives fixed payments for the life of concession with penalties if the road is unavailable (in part or in full) for longer periods than agreed or if KPIs are not met.

**Table 1: Summary of Australian road PPPs by type.**

Name	Year opened	Model	Comment
<b>NSW</b>			
Sydney Harbour Tunnel (SHTC)	1992	Hybrid	Concession design, construct, maintain, with State to operate and toll. State pays SHTC a payment based on traffic revenue, but with a minimum payment to protect downside risk to SHTC
M4 Motorway	1991	Was Full Concession, now Freeway	
M5 South West Motorway	1992	Full concession	
M2 (Hills) Motorway	1997	Full concession	Tolls escalate in excess of CPI
Eastern Distributor	1999	Full concession	Tolls escalate in excess of CPI
M7 Westlink	2005	Full concession	Upside profit sharing
Cross City Tunnel	2005	Full concession	Contribution to the State
Lane Cove Tunnel	2007	Full concession	
WestConnex	???	Not yet known	Will be tolled
<b>Victoria</b>			
Citylink	1999	Full concession	Upside profit sharing
Eastlink	2008	Full concession	Upside profit sharing, KPIs on performance
Peninsula Link	2013	Availability model	
East-West Link	2015?	Hybrid	Proposed to be built and funded as an Availability Model, but will be tolled with revenue to the State. The State may later sell a Right to Toll concession
<b>Queensland</b>			
Logan, Gateway motorways	2011	Full concession	Originally fully government owned and built, now effectively privatised concession. Upside profit sharing, KPIs on performance, UPD (see below)
CLEM 7 tunnel	2010	Full concession	Under receivership. Currently being sold
Airport Link	2012	Full concession	Under receivership
Go Between Bridge	2013	Right to toll	Originally procured by BCC under D&C, fully financed by BCC with tolling contracted but revenue to BCC. Now being sold as “right to toll” concession
Legacy Way	2013	Right to toll	Under construction as D&C contract fully financed by BCC. Now being sold as “right to toll” concession with “cap and collar” on toll revenues

#### **IV. The evolution of PPP concessions in Australia**

One can trace the evolution of PPPs in Australia as going through the following periods over the past two decades. An example of each phase is noted:

- Phase 1: PPP with private negotiation, private sector funding, assured revenue with upside revenue potential based on patronage (SH Tunnel).
- Phase 2: PPP tollroad tendered primarily on lowest toll, full (or part) private sector funding, full patronage risk borne by private sector (M5 South West).
- Phase 3: As phase 2, but also tendered with Key Performance Indicators and penalties for under-performance and with upside revenue or profit sharing (Eastlink)
- Phase 4: As phase 2, but also tendered on size of lump sum contribution to the State (Cross City Tunnel)

The following two phases demonstrate the more recent search for alternate ways to deal with patronage risk.

- Phase 5A: Ways to minimise patronage risk (availability models) (Peninsular Link)
- Phase 5B: Cap and collar arrangement which shares patronage risk and reward (Legacy Way).

There is a link between the procurement options and the appetite of the private sector to accept patronage risk. Early tollroad concessions were bid on higher Returns on Equity (ROE) with higher allowances for risk and were thus more profitable even when patronage did not reach forecast levels (as it often failed to do). In some cases patronage risk was ameliorated by a long concession period and higher than CPI escalation rates for tolls. Later, these two measures disappeared as a result of competition to win bids. As governments became more aware of the profitability of concessions, they sought tighter deals under more rigorous and demanding contracts and the private sector was willing to oblige. Because of the success of some earlier concessions, a bid fever developed with bidders trying harder to win. There is no doubt that a “death spiral” developed wherein bidders placed pressure on modellers to reduce patronage forecasts – the very forecasts which were the key to the viability of their bids.

The key players in the establishment of bid consortia are the bid manager/financial adviser, the equity investor, the constructor and the operator. They come together to form the Single Purpose Vehicle (SPV) which makes the bid. In some cases the operator has been a subsidiary company of the constructor and becomes a sub-contractor to the SPV rather than an equity partner.

The constructor and the financial adviser have little interest in remaining as equity investors in the SPV once construction is complete. In a number of cases, the SPVs have found themselves dominated by the constructors during construction. The constructors and bid advisers then sell their equity and move on, leaving the SPV to deal with its longer term issues, in some cases with little control over the operator and its costs.

Australian governments have become more aware with time of the necessity for the SPV to be able to demonstrate its ability to operate effectively. Consequently, later concessions have

required that the constructor's equity, supported by its balance sheet, remain in place for some period following construction. They have also mandated improved operation and maintenance through the provision of KPIs and performance penalties. These measures have strengthened the arm of the SPV in controlling its obligations.

A further evolution has seen the introduction into two concessions in Queensland of an Upgrade Process Deed which sets out a mechanism for the State to procure additional works either on or adjacent to the concession. The intent is to make such a process easier, quicker and more effective for both parties. Since the concessions have long duration, this facilitates the process of accommodating unforeseen change. For instance, if such a provision had been included in earlier PPPs, the widening of the M5 South West motorway in Sydney may have happened ten years ago.

Note: Dates shown are opening dates, not dates when concessions were let.

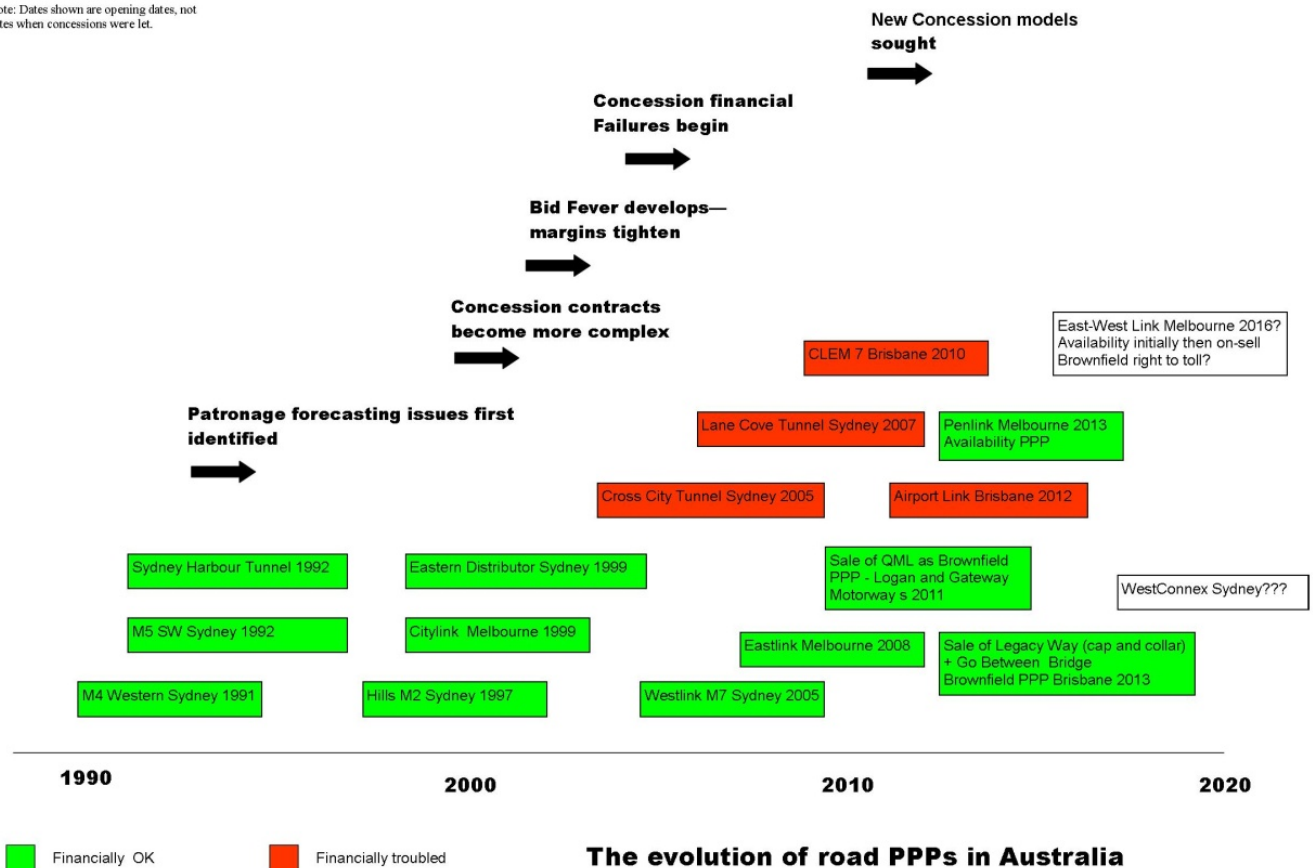


Figure 1. The evolution of road PPP concessions in Australia.

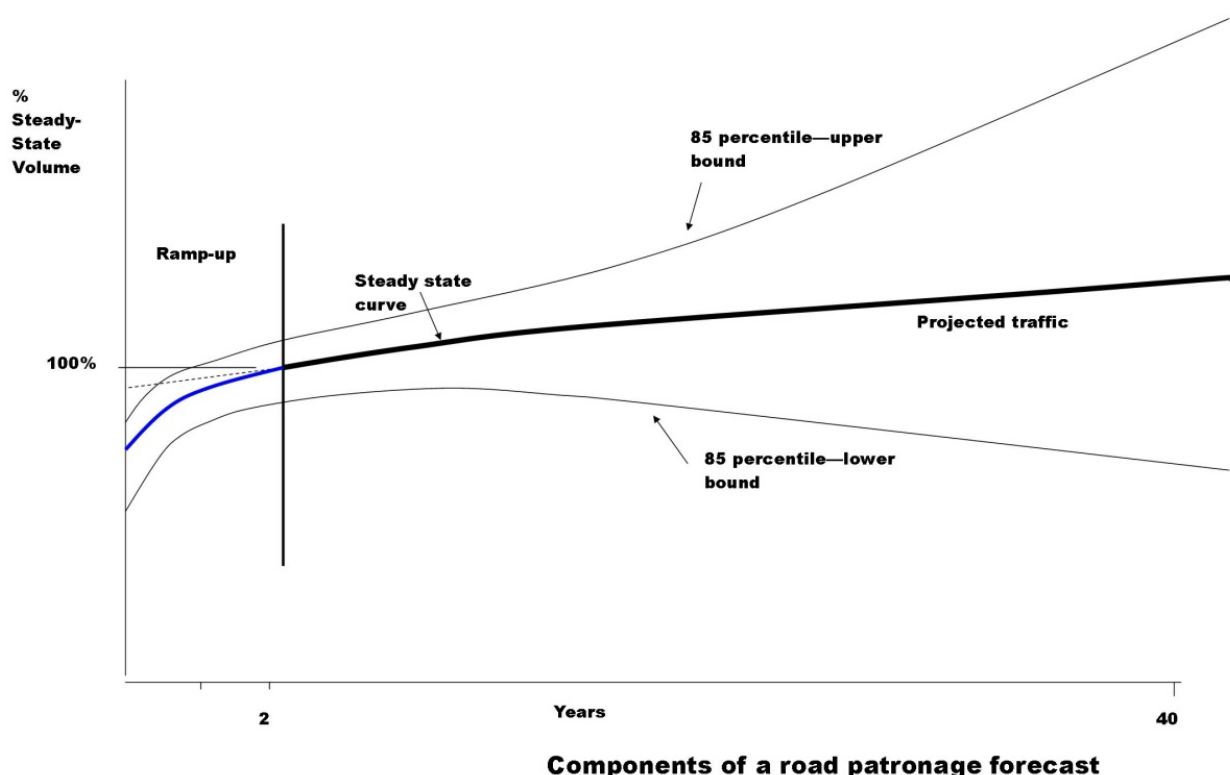


## **V. Australian tollroads and patronage**

This modern era evolution of Australian tollroads is unusual for a number of reasons. All Australian tollroads are intra-urban, whereas most tollroads world-wide are inter-urban. Furthermore, the majority of tollroads world-wide remain in State ownership (often via State-owned companies) and are considerably larger than Australian concessions. The fact that most Australian PPP concessions have required the private sector to accept patronage risk is unusual, though not unique.

Furthermore, most PPPs worldwide have been in sectors other than road infrastructure and are based on availability concepts. Thus the Australian experiment in tollroads has little direct precedent. The forecasting of traffic volumes is a tricky business at the best of times, but the Australian experience has led to increased risks. For example:

- The first stage in developing patronage forecasts is to analyse a network which is toll-free. The second stage is to then adjust using parameters which consider the way motorists value time (in itself, a very difficult process). The first stage sets a level playing field which is subsequently adjusted in the second stage. The second stage compounds the uncertainty of the first stage.
- The models work well on a corridor basis, less well for individual roads within the corridor and even less well for parts of individual roads. The smaller the focus, the higher the likely uncertainty.
- Some small tunnel projects are extremely expensive. Without substantial government funding, this necessitates high tolls to fund the capital expenditure. Individual higher tolls on short distances of road increase patronage uncertainty and combinations of tolls further complicate the decision-making process for motorists, further increasing uncertainty in predicting route choice.
- There may be other (as yet undefined) factors that encourage some motorists to avoid tunnels.
- The network model (without the new road) is verified using the most recent available traffic counts. Thus this model can be considered to be an accurate description of current traffic volumes. The model is then modified to incorporate the new section of road and then projected forward over decades (see fig 2). Projections become less reliable the further forward they look. Concession periods of 40 or 50 years (or more) are extremely difficult to forecast. In many cases, 85th percentile confidence levels can vary from the forecast by 50%.
- The ramp-up period (see fig 2) from opening to “steady state” is not part of the model output. Rather, it is based on judgement, taking into account other ramp-up periods on other roads. The curve commences from an assumed initial traffic volume and merges over a period of 18 months to 3 years with the steady state curve. This is the most critical period in any concession’s life and will make or break the financial support for the concession. Most concessions fail during the ramp-up period if they are to fail.



**Figure 2. Components of a road patronage forecast.**

From Table 2 and Fig 1, it can be seen that accuracy of patronage forecasts does not bear a close correlation with success or failure. A closer correlation is achieved if one looks at the toll per km and the type of asset.

**Table 2. The uncertainty of patronage forecasting.**

Name	Current patronage	Original Patronage vs Original Forecast	Type of asset and length (km)	Current toll per km \$ (see note 1)
<b>NSW</b>				
Sydney Harbour Tunnel	Very high	Not known	Mostly tunnel 4.0	0.50 (see note 5)
M4 Motorway	High at end concession	Satisfactory	Road 12-20? (see note 3)	0
M5 South West Motorway	High	Lower	Road 22	0.20
Eastern Distributor	High	Lower	Mostly tunnel 6	0.50 (see note 5)
M2 (Hills) Motorway	High	Lower	Road (very short tunnel) 21	0.24
M7 Westlink	Good	Lower	Road	0.18

			40	
Cross City Tunnel	Low	Much lower	Tunnel 2.1	2.33
Lane Cove Tunnel	Low	Much lower	Mostly tunnel 3.6	0.84
<b>Victoria</b>				
Citylink	High	Higher	Road + tunnel 22	0.35
Eastlink	Good	Lower, predominantly in the tunnel	Road + tunnel 39	0.15
<b>Queensland</b>				
Logan motorway	Good	Not known	Road 37	0.09
Gateway motorway		Not known	Road + bridge 31	0.07
CLEM 7 tunnel	Low	Much lower	Tunnel 6.8	0.61
Airport Link	Low	Much lower	Mostly tunnel 6.7	0.56
Go Between Bridge	Low	Much lower	Bridge <1	2.88

### Notes

1. Tolls per km are calculated based on the longest possible trip on the concession in a car for an account holder using an electronic tag, taking into account trip caps where applicable.
2. All tolls are current at 19 August 2013 and will change with time.
3. The M4 motorway concession was for only some 6km of road. However, from a motorist's perspective, the perception was more like 12 to 20 km.
4. Tolls on Sydney Harbour Tunnel and Eastern Distributor have been halved since tolls are only applied in one direction.

## VI. PPPs – Score Cards

All PPPs have been very effective in transfer of the following risks from the States: Finance, patronage, D&C, operation, maintenance and customer service. More detail is provided below.

**Debt and equity:** A number of PPPs have overestimated patronage and been unable to survive on original funding arrangements. So far, failed concessions have been resurrected through normal market operations such as refinancing, capital raisings, write downs and transfer of ownership. At no time has any State borne financial risk from a failed PPP, nor has there been any shortage of buyers for failed PPPs.

**Design and Construct:** Variable standards of design, particularly in relation to urban architecture and landscaping (with Victoria so far well above the other States in their expectations and outcomes), some structural issues but, overall, a good to excellent standard of functionality.

**Management:** All PPPs have been reasonably well managed. However, the most successful PPPs have been ones with a strong management, good contractual arrangements (particularly in relation to sub-contractors), a competent, collegiate Board who have developed a very good working relationship with the State.

***Operate and Maintain:*** Variable with some concessions lacking adequate contractual power to ensure a high standard of maintenance, but, overall, a good to excellent standard. The standard of asset maintenance of PPPs is superior to that of the public sector assets. This is not a reflection on the public sector. The private sector PPPs are better able to provision for long term maintenance than are State owned entities subject to the budgeting pressures of government.

***Customer service:*** Very good in all PPPs with this functionality.

***Issues management:*** Overall, very good, especially when there are effective counter-parties within the State. The management of PPP concessions should be a dedicated function within government since these are invariably very complex relationships.

## **VII. Barriers to Future PPPs**

Governments face a number of difficulties in future PPP procurement. Whilst some have been referred to previously, the list includes:

***The huge escalation in the cost of projects*** - There are few corridors set aside for new road infrastructure or even for road widening. Consequently more road infrastructure must be built in tunnels.

***Existing patchwork of highly variable tolls in some states*** (see table 2) - Since each PPP procured so far has been funded independently, tolls vary considerably and can be seen as a barrier by motorists to paying tolls on other portions of the road. The variability of tolls on concessions in NSW is producing unfortunate outcomes. Some tolls are far too high in relation to motorists' perception of value for money and some of the tolls are escalating far more rapidly than others. A re-negotiation and rationalisation of tolls on existing concessions appears inevitable at some time in the future. Victoria has few problems in this regard and Queensland lies somewhere between the other two states. Congestion is enhanced by the patchwork approach.

***Patronage modelling uncertainties*** - There is little confidence that patronage modelling can demonstrate the reliability required by financiers and investors. However, this may be a position which will change with time.

***Public perceptions*** - Because the public's viewpoint is based on the concept that roads should be funded from the public purse, tollroads remain fixed in the public perception as "double taxing". Tollroads must demonstrate value for money to become accepted by motorists. Some do, but this remains a significant political risk. The task of providing the public with sufficient information to gain acceptance of tollroads has not yet

## **VIII. A Way Forward?**

If we accept that PPPs have provided very good value to the States so far, future models should be built on what has been learned from existing models. Future models should contain the following features:

- A contract which encourages innovation in design, community services and operation.
- A rounded and effective consortium for the Single Purpose Entity (SPE) who contracts with the State, comprising:
  - Reputable constructors with real balance sheets and the expectation of a long presence in Australia;
  - Sufficient equity with constructors and bid managers equity participation to extend (say) 12 months beyond opening;
  - A strong financier group in place with Australian Banks well represented. Varied tenor;
  - An operator with a strong track record in operating road infrastructure and managing sub-contractors;
  - Adequate control of the destiny of the SPE. For instance:
    - Contracts for Design and Construction, which has adequate provisions for reporting, truly independent certification and retentions which assure that defects will be addressed promptly.
    - Maintenance and (if sub-contracted) customer service contracts which provide for regular “mark to market” assessments of contracts with provision to terminate if adjustments not agreed;
- All bids being equal, a bid assessed on Return on Equity with the State accepting adequate provisions for risk in the assessment of Cost of Capital; and
- A blueprint for future negotiation of modifications and upgrades to (and adjacent to) the asset.

### **IX. How to deal with patronage risk?**

If patronage risk is to be passed on to the SPE, some means of assessing and rejecting outlying bids becomes necessary. One option is for the State to prepare a patronage forecast and require bidders to bid on that forecast and subsequently accept full patronage risk. The State would set the length of the concession and assess the bids on a bid model ROE and the quality of the bid offerings. It may be difficult to assemble an SPE capable of accepting this risk at this time for any Greenfield project.

Therefore, States might apply a “cap and collar” approach where the State accepts the outlying patronage downside risk and shares upside benefit. The sale of Legacy Way to Queensland Motorways takes this form. However, it only applies to a right to toll concession, construction having been undertaken separately. Similarly in Victoria, the East-West Link may be procured under a similar process, utilising an availability concession for procurement and a subsequent right to toll concession once patronage is established.

An even more radical approach would require a restructure the motorway networks as follows:

- Re-negotiate all existing concessions so that a uniform toll per kilometre is applied to the concessions and to all existing freeways. In Sydney this doubles the length of the tolled network. By having a uniform charge per kilometre, distortions caused by existing tolls are eliminated. The more expensive concessions are cross-subsidised by

the less expensive ones and by the tolls from existing freeways. In this way, patronage risk is amortised over the entire network and becomes almost negligible.

- Apply the considerable revenue stream (after cross subsidies) to the procurement of new assets, preferably using the State's revenue as seeding to capture private sector investment via PPPs.

### **Conclusion**

The procurement by the States using PPP models for road infrastructure in Australia is still maturing, despite setbacks. Since they offer significant benefits to the states, it can be expected that PPPs will form a part of future procurement, though models may well change with time.

# The Care Of Victims: Implications of the Productivity Commission's Proposed No Fault Insurance Scheme

Harrison M<sup>a</sup>

**Abstract:** Traffic accidents impose large costs, with 1,291 road deaths in Australia in 2011. The total costs of road accidents were estimated to be \$17 billion in 2003, equivalent to 2.3 per cent of that year's GDP, averaging around 8.4 cents per vehicle kilometre. The Productivity Commission has recommended replacing tort law with a compulsory, government run first party insurance scheme, where all victims receive compensation from the state, regardless of fault. The proposal is being implemented across Australia, NSW has adopted it this year. Contrary to the PC's assertions, the evidence is that no fault insurance would increase traffic fatalities by 10-30 per cent and accidents by even more. This has implications for the safety design of road infrastructure. An inter-disciplinary approach is taken, in this paper, combining, law, economics and transportation engineering to examine the interaction of legal rules, insurance arrangements, economic incentives and physical infrastructure.

**Key words:** No-fault insurance; Tort law; Third party insurance; Optimal precautions; Activity level; Accident costs

## I. Introduction

In its 2011 "Disability Care and Support" report, the Productivity Commission recommended replacing the current State based disability support schemes with a National Disability Insurance Scheme (NDIS). With attention focused on this plan for multi-billion dollar increases in spending on disability support, and its financing, receiving less scrutiny is the other recommendation in the Productivity Commission's report, that:

*State and territory governments should create insurance schemes that would provide fully-funded care and support for all catastrophic injuries on a no-fault basis, and that would collectively constitute a National Injury Insurance Scheme (NIIS).*

*The NIIS would include all medical treatment, rehabilitation, home and vehicle modifications and care costs, and cover catastrophic injuries from motor vehicle, medical (excluding cases of cerebral palsy associated with pregnancy or birth, which would be covered by the NDIS), criminal and general accidents. Common law rights to sue for long-term care and support should be removed, though access to damages for pecuniary and economic loss, and general damages would remain.<sup>1</sup>*

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Australia  
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The Productivity Commission recommended all states create no-fault motor accident insurance schemes by 2013 and other forms of catastrophic injury be covered by 2015 and an inquiry be held in 2020 to examine widening coverage to damage for pecuniary and economic loss and to some non-catastrophic injuries.<sup>1</sup>

Currently the Northern Territory, NSW, Victoria and Tasmania have no fault insurance schemes for motor vehicle accidents, the other states have fault based tort law liability, where an accident victim can only claim from a negligent injurer (who usually carries compulsory third party insurance).<sup>1</sup> The Productivity Commission's NIIS proposal involves major changes for all. Except for the Northern Territory (which abolished common law rights to sue for transport accidents), the current no fault schemes are 'add-ons', with limited no-fault benefits. They preserve the right to sue for damages under tort law and apply only to motor vehicle accidents. Some require a threshold level of damage to sue under common law; others do not restrict access to tort actions.<sup>2</sup>

The States have agreed to introduce no-fault lifetime care and support for people who are catastrophically injured in motor vehicle accidents prior to the commencement of the NDIS launch.<sup>3</sup> NSW and South Australia have announced plans to convert their compulsory third party car insurance arrangements, where drivers must insure against the risk of being held legally liable to another (the 'third party'), into no-fault schemes – where the driver and all victims claim from the scheme regardless of fault. It includes, therefore, compulsory first party insurance, where the policy holder (the first party) is insured against the risk of suffering loss. The Productivity Commission estimates the NIIS would have cost an extra \$830 million a year in 2011– to be raised from increasing compulsory third party insurance premiums for motor vehicles, medical indemnity premiums, surcharges on rail passengers, levies on boats, increased municipal rates and from general revenue.<sup>1</sup> The Productivity Commission's proposal replaces legal liability with a compulsory, government run first party insurance scheme. The Productivity Commission asserts:

*Nor is there evidence that the common law right to sue for compensation for care costs increases incentives for prudent behaviour by drivers, doctors and other parties.”<sup>1</sup>*

This statement ignores and contradicts the vast theoretical and empirical law and economics literature on the very issues examined in the Commission's report: the effect of tort law and different liability arrangements, insurance, litigation costs, settlement, and no-fault insurance schemes. The Commission's proposal runs the risk of a large increase in accident costs, which can involve substantial negative externalities. A negative externality is an uncompensated net cost imposed by one agent on another without permission. If some of an action's costs are born by other people, then it may be taken even if the social costs are greater than the benefits. As a result external costs may be incurred even if they are not worth incurring. The economic analysis of how tort liability controls harmful externalities is one of the great accomplishments of law and economics. It has moved the central focus of tort law towards how best to induce strangers to take account of the full social costs of their actions and undertake optimal precautions (see Shavell<sup>4</sup>; and Landes and Foster<sup>5</sup>).

## II. The Law and Economics Analysis of Accidents



The economic analysis of accidents starts with the observation that they are not entirely accidental. People do not choose to have accidents, but they can take precautions to reduce the probability and severity of accidents. For example, a motorist chooses what kind of car to drive, how often and what speed to drive it, how often to have its brakes checked, how much to drink before driving and so on. These decisions and many more, affect the cost the motorist imposes on other people.

The law and economics approach further observes that accidents are jointly determined by the actions of all parties involved. The problem is not just to control the injurer's behavior, the victim's actions also affect the probability and magnitude of harm. That is, it uses the model of bilateral precaution. Harm from accidents is probabilistic – whether an accident will occur is uncertain, and the probability of an accident occurring depends on the care or precautions taken by all parties involved. For example, let  $L$  be expected accident losses (for the moment, think of it as being per kilometer and the number of kilometers driven or walked is fixed). The injurer can take a level of care  $X$  at a constant marginal cost of  $C_I$  per unit and the victim can take a level of care  $Y$  at  $C_V$  per unit.

Then  $L = L(X, Y)$ ,  $\partial L / \partial X < 0$ ,  $\partial L / \partial Y < 0$ ,  $\partial^2 L / \partial X^2 > 0$ ,  $\partial^2 L / \partial Y^2 > 0$ . It will be assumed that  $\partial^2 L / \partial X \partial Y > 0$  ( $X$  and  $Y$  are substitutes). The efficient outcome minimises the total social costs of accidents: the costs of prevention, the costs of injuries that nonetheless occur, the costs of administration (such as litigation costs) and the costs of risk bearing. To achieve efficiency, parties should take all cost justified precautions – those precautions that save more in accident losses than the precaution costs. Ignoring litigation and risk bearing costs for now, the efficient outcome minimizes

$$W_X X + W_Y Y + L(X, Y) \quad (1)$$

At the efficient levels of care  $X^*$ ,  $Y^*$  the necessary first order conditions are

$$W_X = - \partial L(X^*, Y^*) / \partial X ; W_Y = - \partial L(X^*, Y^*) / \partial Y = 0.^e \quad (2)$$

It is natural to ask: what set of legal rules will lead the parties to make efficient decisions. It is a complex problem. As the first order conditions show, the optimal level of care by each party depends on the care taken by the other party, and the decisions are taken independently and in advance of the parties' interaction. A decision maker has the incentive to make efficient decisions when faced with the full social cost of his actions, including the cost imposed on others. Then he would undertake actions only if their benefits exceed the social cost. In the jargon, to achieve efficiency we need to internalise the externalities.

### III. The Role of Tort Law

Australia is a common law country, inheriting the body of judge made law built up in England over the centuries. The common law is by far the dominant source of the legal rules that govern the interactions between citizens. Victims enforce the common law and it creates incentives through injurers having to compensate their victims. Tort law deals with externalities between

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<sup>e</sup> The above assumptions about the derivatives of the  $L(X, Y)$  function ensure the second-order conditions are met.

strangers – interactions outside a contractual relationship. A tort is a civil wrong: where one party inflicts damage on another, other than from breach of contract. Contract law deals with breaches of contract, which raises different issues – as the parties can negotiate before the accident and adjust the contract price – and is relevant for medical malpractice and workplace accidents.

One way of inducing people to take appropriate precautions is to make them liable for the cost of the damage they do to others if they don't – by allowing their victims to sue them for damages. That is, tort damages are a way of forcing people to take account of the costs they impose on others. If a party imposes costs on someone else, is sued and held liable – then he must make the victim 'whole'. That is, pay the victim damages, a sum of money that compensates for the damage imposed, transferring the cost back to the person responsible – internalizing the externality to bring private costs in line with social costs.

The main basis for liability for damage from accidents is the tort of negligence. Developed in the nineteenth century, it became important after the invention of the railway, and later the motor car. It imposes a duty to take reasonable care to avoid acts or omissions which you can reasonably foresee would be likely to injure another. Victims must also behave reasonably and take reasonable care – or they will be held to have contributed to the accident and be guilty of contributory negligence. Under the common law, contributory negligence was a defense – the defendant was not liable if the plaintiff was contributorily negligent. In Australia, statute has modified the common law so that a negligent injurer is only partially liable if the victim is also negligent. Contributory negligence reduces the damages paid by the proportion the defendants conduct contributed to the accident – what economists call comparative negligence. For example, if the plaintiff is considered 40 per cent responsible for the accident, damages are reduced by 40 per cent.

#### **IV. How the Rule of Negligence Can Result In Optimal Outcomes**

If the courts set the required standard of due care for each party at the efficient level, the efficient outcome can result. The courts look at the conduct of the defendant and the claimant relative to the norm of the 'reasonable person' to determine whether the defendant should bear the loss, which in practice requires judges to compare the cost of a precaution against its benefit. A reasonable person is obliged to take precautions that are cheap and eliminate a substantial risk, but not expensive precautions against a remote risk. Further, the adversarial nature of common law adjudication encourages the courts to think in terms of incremental changes, focusing on the behavior of the parties. Each party tries to persuade the judge the other party did not act with reasonable care by setting out actions the other party could have taken to avoid the accident. The party accused of negligence counters with reasons why this would not have reduced the likelihood of harm or would have been impractical, too expensive and unreasonable. The court process encourages courts to require only cost justified precautions.

The prospect of being found negligent gives all parties a strong incentive to reach the standard of due care. The following simple model shows how tort can solve the bilateral care problem and result in efficient outcomes. As each party's action affects the results of other parties' actions,

and each makes their decision independently, game theory is the obvious way to model the effects of the law. Consider an accident between an injurer and a victim. Assume:

- Unilateral damage – only the victim suffers damage (think of a car running down a pedestrian).
- Risk neutrality.
- Two levels of care: due care (not liable) or no care (negligent and liable).
- Damages fully compensate victims for their injuries.
- No mistakes. Courts set due care at the efficient level, observe actual care taken and each party knows the required care.
- Fixed number of trips by each party.

Each of these assumptions will be relaxed later in the paper. The payoffs from the care decisions each party must make are set out in the non-cooperative game between two parties summarized in Table 1 (player 1's payoffs are first in each cell). The individual strategies are investment of resources in preventing accidents. Expected accident costs (higher is worse) are  $L(i, j)$  where  $i$  is the motorists action and  $j$  is the pedestrian's action. The cost of taking care for the injurer and victim is  $C_I$  and  $C_V$ . Lack of care increases expected accident costs:  $L(D, D) < L(D, N)$ ,  $L(N, D) < L(N, N)$ . If due care levels are set efficiently, the due level of care reduces accident costs by more than the costs of the care (total accident costs fall when take due care) and so:  $C_V + L(D, D) < L(D, N)$ ,  $C_I + L(D, D) < L(N, D)$ ,  $C_I + L(D, N) < L(N, N)$  and  $C_V + L(N, D) < L(N, N)$ . Combining these gives  $C_I + C_V + L(D, D) < L(N, N)$ .

**Table 1. Negligence game.**

Player 1: Motorist (injurer)	Due care	$C_I$ $L(D, N)$	$C_I$ $C_V + L(D, D)$
	No care	$(1 - b)L(N, N)$ $bL(N, N)$	$L(N, D)$ $C_V$
		No care	Due care
		Player 2: Pedestrian (victim)	

The motorist is liable if he is negligent. If both the motorist and pedestrian are negligent, the pedestrian bears a portion  $b$  of costs, and the motorist  $(1 - b)$ .  $b$  depends on the legal rule in force. Under pure negligence, the injurer is always liable if negligent and  $b = 0$ . The traditional common law rule where contributory negligence is a defense,  $b = 1$ . Under comparative negligence,  $b$  is the share of the victims blame for the accident. Each party chooses the action that maximizes his benefits net of expected liability. As due care is set at the efficient level, a

party that expects the other to take due care will take due care. If the pedestrian takes due care and the motorist does not, the motorist will be found negligent and bear all the accident costs. He has a big incentive to take due care and avoid these costs. If the motorist is expected to take due care, the victim bears all the accident costs and has an incentive to minimize them and take all cost justified precautions.

If  $C_I < (1 - b)L(N, N)$  the motorist has a dominant strategy to take care and the Nash equilibrium outcome is D,D the social optimum where both parties take the efficient level of care. The motorist always takes care, and that induces the pedestrian to take the efficient level of care. For example, this would occur under pure negligence, where  $b = 0$ . The incentive not to be found negligent and liable gives the injurer an incentive to meet the court determined standard of due care. If the injurer takes due care, the accident costs are borne by the victim, who then has the incentive to take an efficient level of care.

If  $C_V < bL(N, N)$  then the pedestrian has the dominant strategy to take care and the outcome is D, D. For example, this would occur when comparative negligence is a defense.

At least one of those outcomes must be true as:

$$C_I + C_V + L(D, D) < L(N, N) = (1 - b)L(N, N) + bL(N, N) \quad (3)$$

So, at least one party has the dominant strategy to take care. The other party expects this and so will take the efficient level of care. Each party has the duty to behave reasonably, but also the right to act on the presumption that others are behaving reasonably. The tort of negligence gives double responsibility at the margin. When the other takes care, each party faces the full social cost of harm up to the required standard of care. The analysis generalises to continuous, rather than two levels, of care. If due care is set at the efficient level, the efficient outcome results.

## V. The Role Of Insurance

Analyzing the effect of insurance requires us to drop the assumption of risk aversion, so that there is a cost to bearing risk and a demand for insurance. For example, in the equilibrium in the simple model of negligence, there is no negligence and no damages paid – so the victims bear the remaining accident costs. That creates a demand for first party insurance. Tort law is bad at providing insurance and compensation, with poor coverage (it covers only a small sub-set of losses: where there is a negligent party to sue) and high legal costs. The accident problem involves not only the goal of appropriately reducing the risks of accidents but also allocating and spreading the risks of losses from accidents that do occur – protecting risk averse people against risk. Risk aversion increases the incentive to meet the standard and can lead to excessive care in the absence of insurance (when care is continuous).

The first best outcome would be for all parties to take the efficient amount of care and for risks to be fully insured and spread; but if an insurance policy completely eliminates risk, it may have an undesirable side effect. It removes the incentive for the insured to take care to reduce the risk of the accident occurring, the so-called moral hazard problem.

If the insurance company can observe the care taken, it can overcome the moral hazard problem by adjusting the premium to reflect the increase in the expected loss resulting from the

insured person's taking less care. When care is not observable by the insurance company, insurance is imperfect and the individual cannot reduce his premium by taking more care, reducing the incentive to take care. If there is moral hazard, the insured takes no care and the probability of the accident increases – this raises the premium. In equilibrium the insurance policy must break even on the care chosen when it is accepted. This may result in the person not insuring at all – if the moral hazard effect of increased premiums outweighs the risk spreading benefits.

What is usually done is to provide partial insurance coverage, such as co-insurance or deductibles or premium increases after claims, in order to induce the insured person to take some precautions – trading off increased care against increased risk bearing. Often governments regulate to prevent insurance companies from doing so. For example, compulsory third party insurance in Australia tends to be uniform with no risk rating or use of co-insurance and deductibles.

## VI. The Effect of No-Fault Insurance

The effect of no-fault insurance is illustrated with the game in Table 2. It keeps the assumptions listed above (such as full insurance), except for risk neutrality. The motorist pays the same premium  $P$  whether he takes care or not, so has no incentive to take costly care. The pedestrian is fully compensated whether he takes care or not, and so has no incentive to take care. All parties have a dominant strategy not to take care. The Nash equilibrium is that neither party takes care, the worst outcome. Accident costs are higher when no-one takes care ( $L(N, N) > L(D, D)$ ) the premium reflects the crash costs when no-one takes care,  $L(N, N)$ . Compared with the outcome in Table 1, drivers are worse off (they now pay a premium that reflects high accident costs) and pedestrians better off (they are now fully insured).

**Table 2. No-fault insurance.**

Player 1: Motorist (injurer)	Due care	$C_I + P$ $0$	$C_I + P$ $C_V$
	No care	$P$ $0$	$P$ $C_V$
		No care	Due care
		Player 2: Pedestrian (victim)	

There is a trade-off between increased accident costs and better compensation and risk spreading. But pedestrians always had the option of taking out first party insurance. If they chose not to because the moral hazard effect increased premiums too much, then it is inefficient to compel their insurance.

## VII. Compulsory Third Party Insurance

In the simple model of Table 1, there is no demand for third party liability insurance because motorists have the incentive to take care; they are not negligent, and not liable. Drivers may be found negligent because of mistakes – they may actually be negligent because they make mistakes in the level of care taken (such as a lapse in concentration) or courts may make errors in assessing the actual care taken and wrongly find an injurer negligent, or the driver may gamble on the court thinking he was not negligent when he really was, and lose.

If care is continuous, court errors tend to encourage parties to take more care, greater than the optimal level, especially if they are risk averse. The higher the level of precautions taken, the smaller the chance of being wrongly found negligent. Risk-bearing is relevant for two reasons: not only because potential victims may face the risk of accident losses, but also because potential injurers may face the risk of liability. The chance of being found liable because of errors by the court or own mistakes creates a demand for third party insurance. Voluntary third party insurance tends to be efficient, even if it is imperfect and reduces care.

There is a trade-off between risk spreading and care – greater risk spreading reduces incentives for care and increases accident costs. But if victims are fully compensated, that cost is internalised in the price of the insurance, which reflects care taken under the policy, and third parties are fully compensated for increase in accidents. Insurance is a voluntary transaction and so it will take place only if both parties believe the gain balances the loss. If individuals choose to purchase insurance, they reveal that the risk spreading benefits outweigh the extra accident costs. If victims are not fully compensated, then they bear some of the extra accident costs and it cannot be guaranteed liability insurance is desirable. Further, if liability insurance is compulsory (as it is in Australia), it cannot be guaranteed that the risk spreading benefits outweigh the extra accident costs.

The Productivity Commission recognizes that no-fault insurance reduces incentives to take care, but it claims that:

*in the presence of insurance, especially with little focus on risk-rating for some causes of injury, the common law does not provide incentives for prudent behavior by motorists and other parties.*<sup>1</sup>

and that no-fault insurance would

*currently perform no worse at deterring excessively risky behavior, as despite the appearance of the common law, it is the insurer that pays.<sup>1</sup>*

That is, the Productivity Commission claims that current compulsory third party insurance removes any incentives for care, so that replacing the current system with no-fault insurance would not increase accidents. But the Productivity Commission ignores a fundamental contribution of the law and economics literature: the model of bilateral care and the importance of victim care. The chance of an accident depends on the actions of both the injurer and victim. Even if we assume full, imperfect compulsory third party insurance, with no risk rating or use of co-insurance and deductibles, and that moral hazard means the insured takes no care at all, tort law still affects the victim's incentive. If the injurer is negligent, the victim may claim compensation from the insurer of the owner/driver of the 'at-fault' vehicle. But if the victim is also at fault, the compensation may be reduced under comparative negligence, providing an incentive for the victim to meet the standard of due care set by the courts, in order to preserve his right to damages. Table 3 illustrates.

**Table 3. Compulsory third party liability insurance.**

Player 1:	Due care	$C_I + P$	$C_I + P$
Motorist (injurer)		$L(D, N)$	$C_V + L(D, D)$
	No care	$P$	$P$
		$bL(N, N)$	$C_V$
		No care	Due care
		Player 2: Pedestrian (victim)	

The motorist pays the premium  $P$  whether he takes care or not, and so has a dominant strategy to take no care. The pedestrian takes care if  $C_V < bL(N, N)$ . As the standard of care is set efficiently,  $C_V + L(N, D) < L(N, N)$ , and so the pedestrian may meet the standard and take care. If  $b = 1$ , as under the common law defence of contributory negligence, then the victim has an incentive to meet the standard of care. Given compulsory third party insurance, the movement from contributory to comparative negligence has a large potential cost, it may reduce victim care, moving the equilibrium from  $N, D$  to  $N, N$ , increasing expected accident costs from  $L(N, D)$  to  $L(N, N)$ . Moving to no-fault insurance removes the victim's incentive to take care, increasing accidents.

More generally, if care is continuous, the victim may have an incentive to take due care under compulsory third party insurance, but if not, he still has an incentive to take some care – more than under no-fault insurance. Victims' care is particularly important in motor vehicle accidents,

where a substantial portion of accidents involve motor vehicles crashing into each other (bilateral damage). In 2010, multi-vehicle crashes were 42 per cent of Australian fatal road traffic accidents.<sup>6</sup> Drivers cannot be sure in advance whether they will be an injurer or a victim. Even with compulsory third party insurance, tort law gives drivers an incentive to be careful in their role as victims – so their damages are not reduced through comparative negligence.

Dropping the assumption of unilateral damage means that tort law gives drivers an incentive to take care even with imperfect compulsory third party insurance. In fact, in the bilateral damage case, both drivers may have an incentive to meet the standard of due care and the optimal outcome is reached. Again, the common law rule of contributory negligence as a defence would ensure the worst N, N outcome, where no-one takes care, is avoided – but it is a possibility under comparative negligence. More generally, some drivers may not have an incentive to meet the standard, but with continuous care they would take more care than under no fault insurance.

The Productivity Commission argues that no-fault insurance will not increase accidents because injurers with third party liability insurance currently have no incentive to take care. But it proposes to extend no-fault insurance to cover all general accidents, such as household accidents, even where injurers do have compulsory third party liability insurance, reducing incentives for injurer and victim care. Moreover, self-inflicted accidents would be covered – such as falling off ladders or single vehicle accidents, which were 44 per cent of fatal road traffic accidents in Australia in 2010,<sup>6</sup> although some of the deaths are passengers. When no other person contributes to, or is involved in, the accident, the costs of these accidents tend to be internalised and efficient levels of accident prevention adopted (the victim and injurer are the same person). Furthermore, people can choose to take out first party insurance and internalize the resulting moral hazard costs. Introducing compulsory no fault insurance for general accidents, financed through municipal rates, will externalise costs to taxpayers, reducing the incentives for care.

### **VIII. Dropping the Other Assumptions**

If courts do not calculate optimal care correctly they will set the standard above or below the efficient level. The parties may or may not meet the standard of due care. If they meet the standard, the tort system encourages them to take some care. If they do not meet the standard, they will be liable, will bear accident costs and have the incentive to take some care. In both cases, tort law gives more care than no fault insurance. Victims have a greater incentive to take care when damages only partially compensate them, so that they bear some accident costs. They are more likely to meet the due care standard (and perhaps even exceed it) and will take some care even under a no-fault scheme. But a no-fault scheme reduces the costs that negligent victims bear, and reduces the incentive to take care relative to tort law with compulsory third party insurance. Injurers have no incentive to take care under either.

A further law and economics insight that the Productivity Commission ignore is the incentive legal and insurance arrangements give for excessive activity levels. Only observable precautions can be made part of the court's standard of due care, and the prospect of being found negligent does not encourage parties to take cost-justified precautions that the court cannot observe. The



activity level is extent of participation in the activity that is the source of the accident, such as kilometres driven. Usually courts do not include the activity level in the required standard of care, either because they cannot observe it or cannot judge whether is excessive. The court can judge whether the driver was negligent in how he drove but not whether he was negligent in how much he drove--whether his marginal trip was worth taking, given the expected accident costs it produced.

Expected accident losses depend not only on the care exercised by each party but also on each party's activity level. For example, the number of car accidents depends on how many kilometres are driven. Under a negligence rule, drivers drive too much, since having taken the efficient level of precaution they are no longer liable for damages. Injurers do not bear the full social costs of their activity, but impose an external cost on accident victims, who bear their accident costs. Injurers only consider their net benefits from extra participation in the activity but not the increase in expected victim accident costs, resulting in excessive activity levels. Under compulsory third party insurance, accident costs that result from negligence are externalised onto the insurance company. But the premium charged to drivers will reflect this cost – internalising this cost for the participation decision (whether to drive at all), which may deter some from becoming drivers (such as young high risk drivers). But as insurance premiums are some fixed annual amount and do not vary with kilometres driven, if the driver chooses to participate, there is still an incentive for excessive activity levels (i.e. to drive too many kilometres), with accident costs externalised across premiums for all drivers. If damages under-compensate accident victims, then they bear some of the external cost as well.

The per kilometre accident externality is significant. Connelly and Supangan<sup>7</sup> estimated the total costs of road traffic crashes in Australia as \$17 billion in 2003, equivalent to 2.3 per cent of that year's GDP. Motor vehicles in Australia travelled an estimated 201,497 million kilometres in the 12 months ended 31 October 2003,<sup>8</sup> so accident costs averaged around 8.4 cents per vehicle kilometre. No fault insurance exacerbates the activity level externality. It increases the accident externality per kilometre through reducing care and covers a greater portion of victim accident costs (externalising more accident costs) – both effects reducing the private cost per kilometre driven (and walked), increasing activity levels. The Productivity Commission do not consider this externality or policies to combat it, such as per kilometre insurance premiums.

## **IX. The Likely Effects of No Fault Insurance**

No-fault insurance will, therefore, increase accidents, even when replacing tort liability combined with imperfect, non-risk rated compulsory third party insurance. No fault insurance increases the accident rate per kilometre and kilometres driven, increasing external accident costs. The Productivity Commission point to the large litigation costs associated with tort law, but the litigation costs may be worth bearing if they cause enough efficient deterrence. The issue is which system is socially most efficient given overall costs and benefits, which include administrative and legal costs. The increase in accidents depends on the importance of victim's care and its response to changes in incentives. Exactly how much deterrence tort law provides and the extent to which replacing the negligence rule with no fault insurance will increase accident costs through reducing care and increasing activity levels is an empirical issue.

The literature finds tort liability provides a significant amount of deterrence, especially for automobile accidents (see, for example, the summaries in Schwartz<sup>9</sup>, Dewees et al<sup>10</sup>; van Velthoven<sup>11</sup>; Sloan and Chepke<sup>12</sup>; and Liao and White<sup>13</sup>). Not the least is the evidence on no-fault insurance. The studies on no fault insurance usually examine the effect of a shift to no-fault insurance on motor vehicle accident deaths, despite many no-fault schemes leaving tort liability intact in death cases. The justification is the probabilistic nature of accidents – less care means more accidents and some fraction will be fatal.<sup>14</sup> The results differ greatly – some finding shifting to no-fault in various states in the U.S. had no effect, others finding a 15 per cent increase in deaths. That is to be expected, as the switch to no fault involves changes in liability rules and in insurance arrangements. The effect of introducing no-fault insurance depends on the system before it was introduced (such as liability insurance arrangements) and the details of the scheme introduced. For example, many schemes (as in NSW and Victoria) retain large elements of tort law and provide relatively modest no-liability benefits. For example, many no fault schemes exclude damages for pain and suffering, and so under-compensate victims (which increases victim care).

The most relevant studies for the NIIS proposal examine the effects of a shift to a pure no fault scheme that abolishes tort liability, as in New Zealand or for motor vehicles in Quebec and the Northern Territory. Swan and McEwin<sup>15,16</sup> present empirical evidence on the switch to no-fault in New Zealand and the Northern Territory, compared to other states of Australia and find it to be associated with a substantial increase of 16 to 20 percent in the number of road fatalities. In Quebec, fatalities increased 3 – 9 per cent (see for example, van Velthoven and Dewees et al).<sup>11</sup> Hause finds little initial effect of the NZ scheme on overall fatality rates, but a modest long run trend effect in increasing fatal accident rates over what they otherwise would have been.<sup>17</sup> Clearly there is a trade-off that the Productivity Commission ignores. No fault insurance may compensate victims better, but is likely to increase accident costs. It is a difficult policy issue – what are the equity effects of helping those with catastrophic injuries, but creating more people in those circumstances? It doesn't help to assume the trade-off doesn't exist.

## **X. Implications for Highway Expenditure**

The prospect of substantial increases in traffic accidents has implications for the safety design of road infrastructure, increasing the optimal amount of investment. If accident costs are  $A = A(H, Z)$  where  $Z$  is dangerous driving (a fall in driver care and increase in kilometres driven increases  $Z$ ) and  $H$  is investment in road infrastructure, where  $\partial A / \partial H = A_H < 0$  and  $\partial A / \partial Z = A_Z > 0$ . If  $H$  costs  $W$  per unit, then if we choose  $H$  to minimise  $A(H, Z) + WH$  then the first-order condition for the optimal level of  $H$ , which minimises accident plus infrastructure costs, is  $A_H(H, Z) + W = 0$ .



An increase in  $Z$  from  $Z_0$  to  $Z_1$  from the introduction of no-fault insurance shifts the  $A(H, Z)$  curve up (from the blue to the green curves) and makes it steeper if  $A_{ZH} < 0$ . This raises the optimal  $H$  from  $X_0^*$  to  $X_1^*$ .

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# **Renewal of Transport Infrastructure in the Context of an Ageing Society in European Cities in the 21<sup>st</sup> Century**

Agnieszka Labus <sup>a\*</sup>

**Abstract:** This article explains how renewal of infrastructure of actual city transport network can provide access of older people to a variety of city areas, including the areas of housing and basic services, in order to prevent the exclusion of older people in society. The author of this article<sup>f</sup> presents, on the base of selected European cities, new and innovative solutions regarding improvement of accessibility to various city areas, including strategic approach to transport policy and renewal of urban spatial planning, in response to the needs of an aging population. Urban development requires proper transportation services, and in turn extension of infrastructure of transport network ensures the availability and increases the attractiveness of the most of city areas for different social groups, including older people, who need special arrangements in this regard. Such feedback makes a mechanism for the development and transformation of urban structures, understood as the renewal of public areas in response to current trends and tendencies in European cities.

**Key words;** Ageing society; Transport infrastructure; Urban renewal; European cities.

## **I. Introduction**

The process of ageing of society has an impact on a number of issues of strategic approach for the future of the city. According to the Charter of Athens<sup>1</sup>, mobility is the key to reducing social exclusion in European cities. In spite of reduction of time of the trip, not all residents feel it equally, due to the limited access to public transport. There is a high proportion of older people using daily public transport, but there are also older people who do not use this service at all - that makes them feel socially excluded. They need solutions that will positively contribute to active ageing, and thus increase their mobility in the city.

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<sup>a</sup> Department of Urban and Spatial Planning, Faculty of Architecture, Silesian University of Technology, Gliwice, Poland ([labusagnieszka@gmail.com](mailto:labusagnieszka@gmail.com))

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Transport infrastructure renewal, according to the OECD<sup>1</sup> sees solutions in systems of integration services, reduced spatial distances, contributing to a more compact urban structure in the development of future cities, thus supporting economic growth and urban renewal. There are many links for the transport infrastructure in the sustainable development, among them the most important seem to be two aspects. On the one hand, urban streets, should not only allow the smooth movement of vehicles, but also presence of public spaces, social, with a small architecture, frontages, bike paths, etc., providing accessible and safe access to various locations in the city. On the other hand, the grid of streets in dense urban multifunctional structure can be part of supporting and stimulating older people to activity based on social networking in local venues and local services. The appropriate density of development and the street grid reduces the need to transport and makes the use of infrastructure more efficient.

Transport infrastructure renewal in European cities generally includes activities related to the removal of physical barriers and possible separation of pedestrians from traffic. However, there is a need for broader changes in this area, because the older generation may have special needs in terms of structure and function of the urban environment. The importance of the availability of local amenities increases with age. For example, older people make everyday shopping on foot, so the connection with the services should be located within walking distance of their home, that results in the need for a well-designed network of sidewalks and paths. The ageing of the population also contributes to the increase in demand for services and articles aimed at a specific age group<sup>2</sup>, reduces the amount of time spent on a job and makes a rapid change in social structures<sup>2</sup>. More and more people, due to the increased mobility<sup>3</sup>, use the services of the neighboring towns, that is associated with an increase in competition between the cities and the necessity to develop easy links to other urban centers and the related dense network of public transportation.

## **II. Case studies**

The subjective selection of case studies includes representative European cities, where the author was involved in the process of renewal of infrastructure of the city transport network. These studies present examples of the strategic and structural approach in selected European cities, such as: Barcelona (Spain), Malmö (Sweden), Sangerhausen (Germany), which are the cities that provide urban renewal policy in the context of demographical changes.

### **I. Barcelona (Spain)**

Barcelona is one of the European cities which carry on urban policy aimed at the renewal of the city in the context of an ageing of the population. The city participated in a global project “Age Friendly Cities”, which aim to change the way of thinking about the city in the context of adapting it to the needs of people of all ages. As an participant in project “Age Friendly Cities” Barcelona conducted a study on daily life and experiences of older people in the city<sup>4,5</sup> and today is considered to be one of the cities in which they live the most comfortably and where one can easily move around. The changes that were introduced in the city in order to adapt it to the needs of the residents had been planned for the motto: “do not - for cars, do - for pedestrians”.

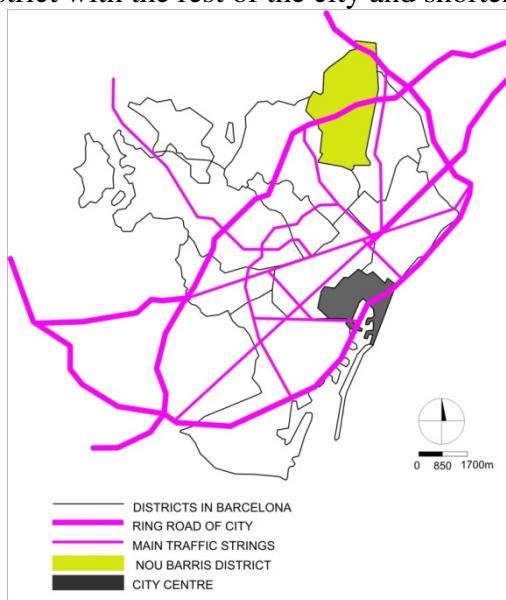
#### *Strategy approach*

In Barcelona, the main objectives of transport policy in the context of older people were:

- creating pedestrian-friendly areas by eliminating cars from the pedestrians zones in the city, in which they are the main problem increasing the risk of accidents and reducing level of security,
- the introduction of new public transport to facilitate access to specific functions in the city, in the end, a relief for public transport for the elderly in the form of special cards “Rosa Target” and new forms of so-called bus El Barri del Bus, the bus to the nearest neighborhood residential areas and Nocturn bus, or buses in the night. Buses from the neighborhood support a large number of stops in the city, and their distribution is dense, which is significant to facilitate and enable the mobility of the elderly and disabled<sup>6</sup>,
- expansion of the existing system of bicycle paths, aimed at promoting a healthy lifestyle and a more ecological means of transport (to encourage older people to be active).

#### *Structural approach*

Urban renewal of transportation activities in Barcelona (in this article) applies to urban structure Nou Barris district, located in the north of Barcelona, which is characterized by a topographically diverse terrain. The potential of the area has increased in 1992, when in connection with the Olympic Games in Barcelona a ring road was built, that connected the district with the rest of the city and shortened distance between the districts of Barcelona.

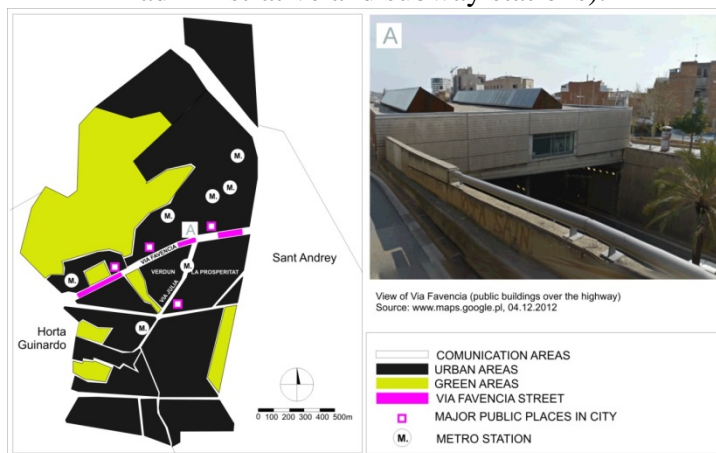


**Figure 1.** Main arterial roads and the neighbourhood's connections with the city centre.  
Source: author on the basis of [www.mapy.google.pl](http://www.mapy.google.pl)

The demographic situation in the district made an extra boost to its renewal, because 30% of the population in Nou Barris district are elderly people. Significant differences in elevation of land in the district represented spatial barriers that in the context of older people contribute to their exclusion from urban and social life. There was no friendly public spaces which are places for meeting and recreation for the elderly, because most of them were crossed by major transport

routes. Location of bus stops of public transport prevented access to basic services, there was also lacking space for recreation close to home<sup>7</sup>. Due to the topography of the land in Nou Barris district, a big problem for residents, especially the elderly, was the availability of the bus, metro and core services. There were lacking pedestrian zones, and transport services were not well distributed, due to differentiation of terrain. Public buildings were located too far away from residential areas, beyond the reach of the elderly. Older people were forced to use other than public means of transport (taxis), or stay at home. The main aim of renewal of communication areas was to connect the district to the city center and the integration of the two settlements Verdu and Prosperitati with walking pass by the Via Julia. On the Via Julia meeting place for the elderly, along with direct access to the metro and bus stops was located. In addition, in the structure of the district a system of three passageways was designed, forming links between housing estates, such as:

- pedestrian walkway with local services,
- city squares forming a meeting place for the elderly, connected by walkway crossing the district and allowing the opening for the new areas),
- pedestrian connection with the revitalized pedestrian settlement (inhabited mainly by senior citizens) and the rest of the city (introduction of new public buildings, administrative and subway stations).



**Figure 2.** Connections of public spaces between the housing estates of Nou Barris neighbourhood. Source: author.

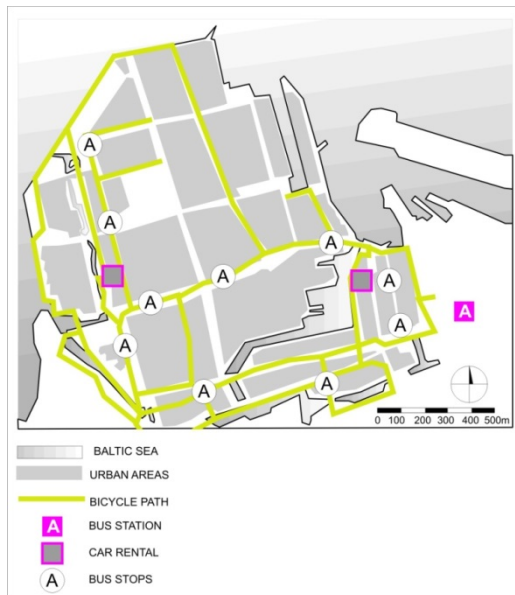
## II. Malmö (Sweden)

City of Malmö is located in the Öresund region in Sweden and it is the third largest city in the country with a population of about 300,000 inhabitants. A large part of them are the people of other nationalities, reflecting the multi-cultural character of the city. People over 65 years of age account for about 16% of the general population and young people (under 45 years old) account for about 62%, hence the city of Malmö is classified as a young from demographic point of view. However, it is an example which is worth a more detailed presentation, due to its policy of renewal, taking into account the urban aspect of the aging population.

### *Strategy approach*



Key investment was the construction of the Öresund bridge, that has increased the city's importance in the region, and even in Europe and created the potential for the development of the city, new investments, new jobs, new residential areas, which contributed to the attractiveness of the area. Malmö residents, including the elderly, due to this connection may use the services offered by Copenhagen, which is a large metropolis, offering a wider range of important service and cultural and educational chances for the elderly. The municipal authorities in order to facilitate the mobility of older people in Malmö have introduced a system of coordination of transport, which aims to maintain a high standard of service and optimizing the performance of vehicles. Significantly reduced number of parking spaces resulted in a creation of public space free of cars. Some streets were closed to vehicular traffic with pedestrian traffic entering only. The city has also a well-developed network of bike paths providing fast, eco-friendly and economical way to get around the city center of urban canyons. The activities included the construction of urban bike paths along the main roads in the city center<sup>9</sup>. Such a policy successfully reduced traffic in central city areas and designated new areas of public life. According to the communication strategy regarding cycling in the city, an increase in bicycle transport can play a key role in creating sustainable development of Malmö.



**Figure 3.** Areas served by public and bike transport in Västra hamnen neighbourhood in Malmö. Source: author on the basis of Folett N., & Filed S., (2011), *Europe's vibrant New Low Car(bon) Communities*, ITDP, Malmö<sup>8</sup>.

#### *Structural approach*

The transport system is designed to promote eco-friendly transport in Malmö. This is accomplished by bus, by bike or by foot. Bo01<sup>8</sup> area has been designed to minimize the need to

<sup>8</sup> **Bo01 area** (also known as the "City of Tomorrow") was a housing expo in the southern Swedish city of Malmö. It was created in 2001 as part of the European Housing Expo and is notable for its sustainable character.

move the car. The main mean of transport within the estate are specially rented bicycles and electric-powered vehicles. A dense network of cycle paths provides access to any part of the district in the city. Moreover in the city a convenient for residents, developed bus system was organized. Bus stops in the district of Västra Hamnen are located in close proximity to residential areas, along major traffic routes in the district, at approximately 400 meters. In the Bo01 district one can rent a car driven by electricity, in order to promote healthy living environment (without the noise and pollution), that promotes a high quality of life for all residents. Parking spaces for cars have been placed outside the team, and in several underground car parks, which reduces the danger of accidents on the streets, in which frequently participants are the pedestrians.

### **III. Sangerhausen (Germany)**

Sangerhausen is a city located in the southern part of the region Saxony-Anhalt in central Germany. It is one of the oldest cities in this region, with a population of about 30,000. It has a long tradition of heavy industry, especially mining. In connection with the liquidation of mines there was a big wave of emigration due to lack of workplaces, resulting in a large number of vacancies. This was associated with a decrease in population in the city, which has contributed to the process of shrinking and ageing of the population. Demographic projections predict that the situation will get worse, which can cause adverse effects on the development of the city. Currently, elderly people above 65 years of age account for about 26% of the population<sup>10</sup>.

#### *Strategy approach*

The local transport plan<sup>11</sup> for the district Mansfeld Südharz, in which Sangerhausen is located, has included a chapter on the impact of demographic changes on mobility. The document noted that, due to an aging population and an increase in the number of single person households, people are increasingly changing their place of residence in old age and are characterized by higher activity in the elderly, resulting in expected in the future increase in the number of elderly travelers, less likely using public transport, and often other forms of transportation. In addition, growth in single person households will increase the demand on the system of services delivered to homes, particularly during working hours, which is the opposite of the current trend, when the most traffic is generated after those hours. It is expected that as a result of demographic changes, the public transport will lose in importance. Now in the district of Mansfeld Südharz declining trends related to the intensity of use of public transport are observed.

#### *Structural approach*

Sangerhausen city is well connected in terms of access to neighboring towns. The main means of transportation include: the train, the communication bus service in the city and outside its borders, and a well-developed network of roads and highways. Transportation in the city is serviced by city buses, plying on three lines. Supra-local transport is provided by the railway as well as an additional buses to neighboring cities such as Halle, Nordhausen, Magdeburg and Erfurt. This allows older adults can benefit from service offers of the neighboring municipalities.

### **III. Conclusion**

The above presented case studies made it possible to draw conclusions regarding the methods of renewal of the city transport network.

In Barcelona transport infrastructure renewal has been carried out on the basis of following interventions:

- point interventions (multi-generation housing estates, nursing homes for the elderly),
- linear interventions (promenades for pedestrians, means of reaching one's destination),
- system interventions (relationship between functional-spatial structures, with particular emphasis on the effective distribution of services in the area, with the ability to reach them by foot).

Those interventions have contributed to the synergies between the different functional-spatial structures, so that the entire structure of the district was integrated not only with the nearest surroundings, but also from the city center, which offers older people a wide range of commercial services, culture, entertainment, etc. In turn Malmö implements the concept of a compact and green city, growing within the urban structure. Older people have access to different services by reducing traffic in pedestrian zones and creating a compact structure of communication areas, providing access to basic functions by foot, or in close proximity to bus stops of public transport and also by mixed utilization of areas with different functions.

In case of Sangerhausen the transport system in whole city scale is underdeveloped. This is due to short distances between particular areas in the city, which can be covered by foot. The frequency of plying of public transport is less than in other big cities. The number of lines of public transport is small, and their routes cover all areas of the city. This type of transportation is addressed to people who want to get to distant areas of the city, without paying excessive attention to the time of trip and the frequency of plying.

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# Metamorphosis: Grid 2.0 Emerging at the Edge of the World

Roger Bradbury<sup>a</sup>  
Fred Popowich<sup>b</sup>

**Abstract:** Were we to rebuild the power grid today, we wouldn't build the one we have. We would build a resilient, non-hierarchical network, smart and adaptive at every node, with diffuse and multi-scaled power producers and consumers. If this is the Grid 2.0, can we find an evolutionary path to it? This profound complex systems problem no feasible adjacent possibilities for Grid 1.0 is typically solved by evolution through metamorphosis. Caterpillars become butterflies by breaking down the caterpillar system into its base components and reorganising (most of) them into a new butterfly system. But this can only be done in the quiet edges of the enveloping super-system Stewart Brand's outlaw regions. We're taking the first steps to metamorphose Rarotonga's grid in the remote Cook Islands of the South Pacific. Here the conditions are just right. We invite collaboration to help realise our vision and its transpose lessons for the super-system's centre.

**Key words:** Smart grid; Sustainability; Critical infrastructure; National security

## I. Introduction

If the world had its druthers, it would not build today the electricity grid it inherited from yesterday. That grid — let's call it Grid 1.0 — was built for a 19<sup>th</sup> century world and was adapted progressively to the needs of the 20<sup>th</sup> century. The build was constrained by the laws of physics, but it was also constrained to fit an evolving socio-economic system. And as a result it, too, became a complex adaptive system, a creature of its history, adapted to its environment, and subject to iron laws of evolution.

Grid 1.0 emerged — and we use the word in its complex systems sense — at the end of the 20<sup>th</sup> century in a form fundamentally ill-fitted for its current function. Evolution fits systems to the recent past not the future. But the 21<sup>st</sup> century earth system has step-shifted through the ongoing process of globalisation<sup>1</sup>. We struggle from within this system to describe the changes showering down on us. But there is no denying that the earth system has changed in fundamental ways in both its biophysical and socio-economic dimensions. The word 'revolution' is much used – the internet revolution, the 'just in time' revolution, the nanotechnology revolution, the

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<sup>a</sup> National Security College, Australian National University, Canberra ACT 0200, Australia

<sup>b</sup> School of Computing Science, Simon Fraser University, Vancouver BC V5A 1S6, Canada  
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biotechnology revolution — not to mention the Anthropocene, climate change and the Arab Spring.

And more change is on the way. The 21<sup>st</sup> century socio-economic system is not settling into any sort of equilibrium, much to the consternation of the economists who need the assumption of equilibrium in order to model the economy. Rapid, disruptive, perhaps accelerating, change is the new normal. Grid 1.0, if it is adapted to anything, is not adapted to these sorts of changes<sup>2</sup>.

So a fundamental question for our century is whether Grid 1.0 can now evolve to fit the newly-emerged globalised world, and its social, economic and physical characteristics. It's fundamental because Grid 1.0 sits at the heart of the critical infrastructure of any advanced society. The proper functioning of our critical infrastructure is a key determinant of our welfare and prosperity — our national security.

One might put up the counter argument that the continuing existence of Grid 1.0 proves that it has evolved to fit the 21<sup>st</sup> century, but that is not the case. Many systems become dinosaurs, reaching the limit of their adaptive capacity, surviving for a while through sheer inertia before becoming extinct. We argue that the evidence shows that Grid 1.0 is just such an object. The earth system, Grid 1.0's ultimate super-system, has achieved its present globalised state — flat, hyper-connected, interacting, high-frequency and fast-changing — by all sorts of work-arounds despite, not because of, Grid 1.0. The link between the Grid 1.0 and the global socio-economic system — its immediate super-system — is jury-rigged to accommodate Grid1.0's incapacity to change. It must reach a tipping point soon<sup>3</sup>.

Overlaying Grid 1.0 with 'smart grid' technology has been heralded as a solution to the inherent physical challenges of the existing infrastructure. Mechanisms for distributed control and even end-user participation<sup>4-6</sup> may provide technical stop-gap measures, but the problem with Grid 1.0 is more than a technical problem, as seen by large scale resistance to the introduction of smart meters by many utility companies.<sup>7</sup>

#### **A. If Grid 1.0 is the problem, metamorphosis is the solution**

Our argument here is twofold. We say that Grid 1.0 has reached the end of its evolutionary tether — it has nowhere it can really go. We need a new grid: Grid 2.0. Furthermore, we argue that the only feasible way for a new grid to emerge is through a process we call metamorphosis. Instead of adding more bells and whistles to Grid 1.0, we need to break it down into its low-level building blocks — its atoms, if you will — and reassemble (most of) them in new ways.

We choose the metamorphosis analogy deliberately. Metamorphosis is how evolution solves the problem of fitting an organism to a dramatically different environment, whether it is a caterpillar metamorphosing into a butterfly, a planktonic phyllosoma larva into a lobster, or, most amazingly, a bilaterally-symmetrical planktonic brachiolaria larva into a pentaradially-symmetrical starfish. We think metamorphosis offers a path for all complex adaptive systems, not just living ones, out of evolutionary quandaries.

Interestingly, it is only now that we think that it is possible to metamorphose the electrical grid.

At the end of its life, Grid 1.0 has thrown up some possibilities that are only just becoming apparent. In a curious way, its current failures are helping create the environment for the emergence of Grid 2.0. They are doing this not by providing a smooth path for an incremental transformation, but by providing new building blocks, new atoms, which can be used in the metamorphosis. So the vast effort on political, financial and intellectual fronts that has been made thus far on many futile ‘smart grid’ projects has not been entirely wasted.

This work has created a host of new components from which a grid — any grid — may be built. We now have in the world a range of energy sources at many scales, new sorts of storages again at many scales, extensions of the reach of the grid into transportation, and the beginnings of more subtle uses of the power of the grid, once more at all scales, through the injection of information everywhere into the grid<sup>8</sup>.

Of course Grid 1.0 has countered these new components at almost every turn by system feedbacks that attempt to nullify the attempted change. This is to be expected. The present grid is tightly adapted to a stable world, and is quite brittle in the face of perturbations. We have seen enough cascading failures — a classic symptom of a complex adaptive system outside its comfort zone — to know this. But perturbations are a canonical feature of today’s world and, likely, of future worlds<sup>9-10</sup>.

So even if these new components are not used, or only grudgingly, by Grid 1.0, their mere existence is enough. A richer set of building blocks makes the metamorphosis task easier. Indeed, we argue that at the end of the 20<sup>th</sup> century, the task was almost impossible. It looked as if the earth system might be burdened with a dysfunctional grid through to the middle of the new century. Now, with the possibility of metamorphosis and a richer set of atoms, the task is merely daunting.

## **B. The nature of the metamorphosis task**

To better understand the nature of the task, we need to consider, at a very high level of abstraction, both the nature of today’s grid and the nature of the enveloping system in which it is embedded.

Profoundly, Grid 1.0’s connectivity is wrong for today’s world. Both the biophysical and socio-economic systems that together comprise the earth system are non-hierarchical at more or less all scales, and are likely becoming more so. Most critical infrastructures are evolving in the same way, often creating robust scale-free networks, like the internet, financial services or transportation networks. They are responding to the increasing variability of their environment. Indeed, we argue that one of the most fundamental properties of any critical infrastructure in the Anthropocene has to be resilience and that that is most likely achieved through scale-free networks<sup>11-12</sup>.

But today’s power grids remain resolutely rooted graphs and so remain hugely sensitive to perturbations. While there have been proposals to integrate microgrids incorporating distributed generation to allow Grid 1.0 to evolve into a smart grid (e.g. Erol-Kantarci, Kantarci & Mouftah<sup>13</sup>), there is almost no way to smoothly change a rooted graph to a scale-free graph, so that this property of Grid 1.0 alone confirms the need for metamorphosis.

Grid 1.0's entropic structure also sits awkwardly with the entropic structure of the Anthropocene. Today's power grids are simple rivers of energy, cascading and dissipating as they spread from relatively few large sources to numerous sinks. Households or communities that use wind or sunshine to produce small amounts of energy are often viewed as troublesome sinks that frequently clog, pushing dirty water back into the local community. Our power grids are a tribute to the triumphs of 19<sup>th</sup> century thermodynamics, but sadly of declining utility in the 21<sup>st</sup> century Anthropocene. They are simple machines when today's requirement is for more lifelike systems. We've known since Schrödinger<sup>14</sup> that lifelike systems exist primarily in the eddies of energy cascades where negentropy or information can get some leverage. Scale-free and other non-hierarchical networks create such eddies — feedback cycles really — and so allow information and ultimately intelligence to gain purchase on the system.

It is no coincidence that non-hierarchical critical infrastructures are evolving to become intelligent while today's power grid resists this trend despite attempts to bolt-on 'smarts'. The connectivity structure of non-hierarchical systems gives negentropy somewhere to live, creating the conditions for intelligence to emerge. There is nowhere for negentropy to live in an hierarchical power grid optimised to increase the efficiency of its energy cascade.

We argue that a grid fitted to the Anthropocene, Grid 2.0, should have information everywhere. It needs this so that it has the capacity to become aware autonomously and at all scales.

Another feature of the Anthropocene that is not mirrored — cannot be mirrored — in Grid 1.0 is what we might call evanescence. It arises from the today's faster cycle times of both the biophysical and socio-economic systems together with the spikes and perturbations that the clash of these cycles brings. It means that old connections between components of these systems break and new ones reform continuously and at all scales. Unlike Grid 1.0, which gives primacy to the integrity of the network, Anthropocene networks are evanescent. Such stability as they have is a dynamic, emergent, often evanescent property functionally distinct from the static neutral stability sought by Grid 1.0.

So the grid for the Anthropocene needs to be more or less scale-free and self-similar, with production, consumption and storage of energy at all scales, with feedback loops at all scales to allow power to flow in all directions and to allow for the emergence of intelligence, and with the capacity to break and reform links autonomously.

This is an engineering task for the physical grid and the enveloping biophysical and socio-economic systems that only metamorphosis can achieve.

### **C. Why Rarotonga is beautifully edgy**

But we have a problem in executing this task, in creating an exemplar of Grid 2.0 from which memes can spread. The problem is so urgent that it needs more than toy solutions found in laboratory simulations or small greenfield settings. It needs a metamorphosis of a real existing grid. And this in turn creates two problems, one theoretical and one intensely practical.



The theoretical problem is well-known. It is the tendency of larger complex adaptive systems to consume neighbouring smaller ones. Ramón Margalef<sup>15</sup>, the great theoretical ecologist first formalised this, but it has been observed, if not understood, in social systems by historians from the time of Thucydides. Stewart Brand<sup>16</sup> acknowledged this phenomenon in his ideas about the locus of innovation. New ideas, Brand thought, come from the edges of systems, from outlaw country, from the frontier, where they can get a chance to grow.

And this problem is reinforced, or perhaps it is merely expressed, by the practical problem of asking an owner of a major grid to take their system, break it down and metamorphose it. The immediate response is a nervous no, a disbelieving no, an astonished no, but in all cases, no.

So we need to turn to somewhere at the edge of things, where there is a frontier approach to life, where there is a high motivation to try new things because of the crippling cost of power, and where the world is lightly regulated: somewhere which is the right size — a society not just a community but yet nicely scaled, and, most importantly, where metamorphosis of the current grid would make a major positive difference to the society.

Rarotonga, in the Cook Islands, fits the bill admirably.

#### **D. Metamorphosis, Grid 2.0 and Te Aponga — the story so far**

The Cook Islands are a small independent Polynesian state in the South Pacific in free association with New Zealand. Rarotonga is the most populous island with its main town, Avarua, the nation's capital. Rarotonga's electricity grid is owned by a public utility, Te Aponga Uira O Tumu Te Varovaro, known to the locals as TAU or just Te Aponga. Te Aponga generates, distributes and retails electricity from a single power station in the Avatiu Valley using a bank of eight diesel generators. It is a classic rooted network with six main high-tension feeder lines from the central generation site and subsidiary lines branching off from those main feeders. There are about 4000 consumers connected to the grid, with the most of the electrical consumption used in support of the tourism industry.

Rarotongans pay hugely over the odds for their power. The diesel to run the generators must be imported, expensively, from New Zealand 3000 km away. Currently Rarotongans pay about \$0.90 per kWh (compared to an expensive ca. \$0.20 per kWh in Australia). This *very* expensive power is a major drag on the economy of this developing country, preventing private enterprise from flourishing. It contributes in a significant way to the ongoing depopulation of the Cook Islands, as young Cook Islanders leave their country for New Zealand or Australia where they can get a job and enjoy a reasonable cost of living<sup>17</sup>.

But Rarotongans, like other Polynesians, are a resourceful people and can draw on their strong community traditions — often called 'the Polynesian way' — to solve hard complex problems collectively.

The Murienua district in Rarotonga is where these cost pressures have met these problem solving traditions leading to a community project to metamorphose their grid. The Murienua Power Cooperative, led by its energetic chair, James Beer, a local businessman, has begun work

with a Canadian technology start-up, Sweet Lightning, Inc. Sweet Lightning, in Cook Islands Maori, is roughly ‘electricity from the sun’.

This work involves creating, in the first instance, a smart street in Murienua, with a mix of neighbourhood sinks, sources (mainly solar) and storages (pumped water storage with microhydro) for power<sup>17</sup>. All the neighbourhood devices will be aware of each other and able to respond adaptively to local changes in supply and demand of power. They’ll be connected in a resilient mesh. The street will be linked to the main grid by a single line, held at the appropriate tension but with no net flow in either direction.

Our economic modelling shows clearly that the consumers in the street will pay the Murienua Power Cooperative much less for their power than they currently pay to Te Aponga. The Cooperative will price its power above its break-even price but significantly below Te Aponga’s price, and the profit will go into an evergreen fund to be used to deploy the model to other streets in the neighbourhood, and so on until the Cooperative is servicing all the consumers on one feeder line. The intention is then to reproduce the scheme in a similar way on another feeder line with the ultimate aim of creating Grid 2.0 on Rarotonga.

The first solar panels have been installed in the street. The site for the pumped storage has been secured, using an existing large cistern at 200 m elevation and fed by a mountain stream with an already existing large diameter supply pipe. Economic modelling is underway. Sweet Lightning is developing the software necessary to create a ‘community’ of intelligent agents to control such a grid.

Watch this space!

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# Energy Efficiency Dashboard for Small Businesses in the Illawarra

M. Safadi<sup>a\*</sup>  
J. Ma<sup>a</sup>  
R. Wickramasuriya<sup>a</sup>  
V. Somashekar<sup>a</sup>  
O. El Fakih<sup>b</sup>  
L. Yalan<sup>b</sup>

**Abstract:** Energy consumption by small and medium enterprises (SMEs) is increasingly becoming a matter of profitability for many businesses and a source of concern for Government agencies. Recognizing the need to improve SME's energy consumption, the NSW - Office of Environment and Heritage (NSW-OEH) has successfully implemented a business-focused energy efficiency program. The program involved individual audits conducted by certified assessors, estimating actual energy use by appliances and providing recommendations for retrofitting of more energy efficient equipment. The SMART Infrastructure Facility and the NSW-OEH have partnered to create an online and interactive data portal (the Energy Efficiency Dashboard – EED) that brings together information collected throughout the energy efficiency program in order to better inform other business managers about the opportunities to improve their profitability and sustainability. This paper demonstrates how the Energy Efficiency Dashboard, a fusion between Business Intelligence and Geographic Information Systems, can provide a robust, highly interactive, online analytical dashboard to evaluate the effectiveness of the energy savings program. Uses of the EED include identification of business-specific best energy saving appliances and practices, business types with high potential for saving energy, and benchmarking energy use across business types.

**Key words:** Dashboard; Energy efficiency; SME.

## I. Introduction

Small and medium enterprises (SMEs) shape a significant and important part of the Australian economy. In 2011, there were approximately 1.96 million actively trading small businesses in Australia comprising 96% of the total businesses. SMEs account for over a third of the total production, and employ around 50% of the private non-financial sector, 33% of these businesses are located in NSW<sup>1-2</sup>.

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, NSW 2522, Australia

<sup>b</sup> NSW - Office of Environment and Heritage, Level 2, 1 Fitzwilliam Street, Parramatta, NSW 2150, Australia

\*Corresponding author: Murad Safadi [murad@uow.edu.au](mailto:murad@uow.edu.au)

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The Australian Industry Group (Ai Group) conducted a survey on energy efficiency of businesses throughout April and May 2012, which targeted all sectors and states with a total of 319 respondents<sup>3</sup>. Results showed that the amount businesses spent on energy increased between 2008 and 2011 which negatively affected businesses' profitability. Further, the survey indicated that NSW and SA businesses have been affected the most. As a result, NSW and SA businesses were more proactive than other states to take steps to improve their energy efficiency to reduce energy costs. Reducing business expenditure is one of the main motivations for businesses to take energy efficiency actions. The most common action taken was to change the staff practices towards energy consumption<sup>3</sup>.

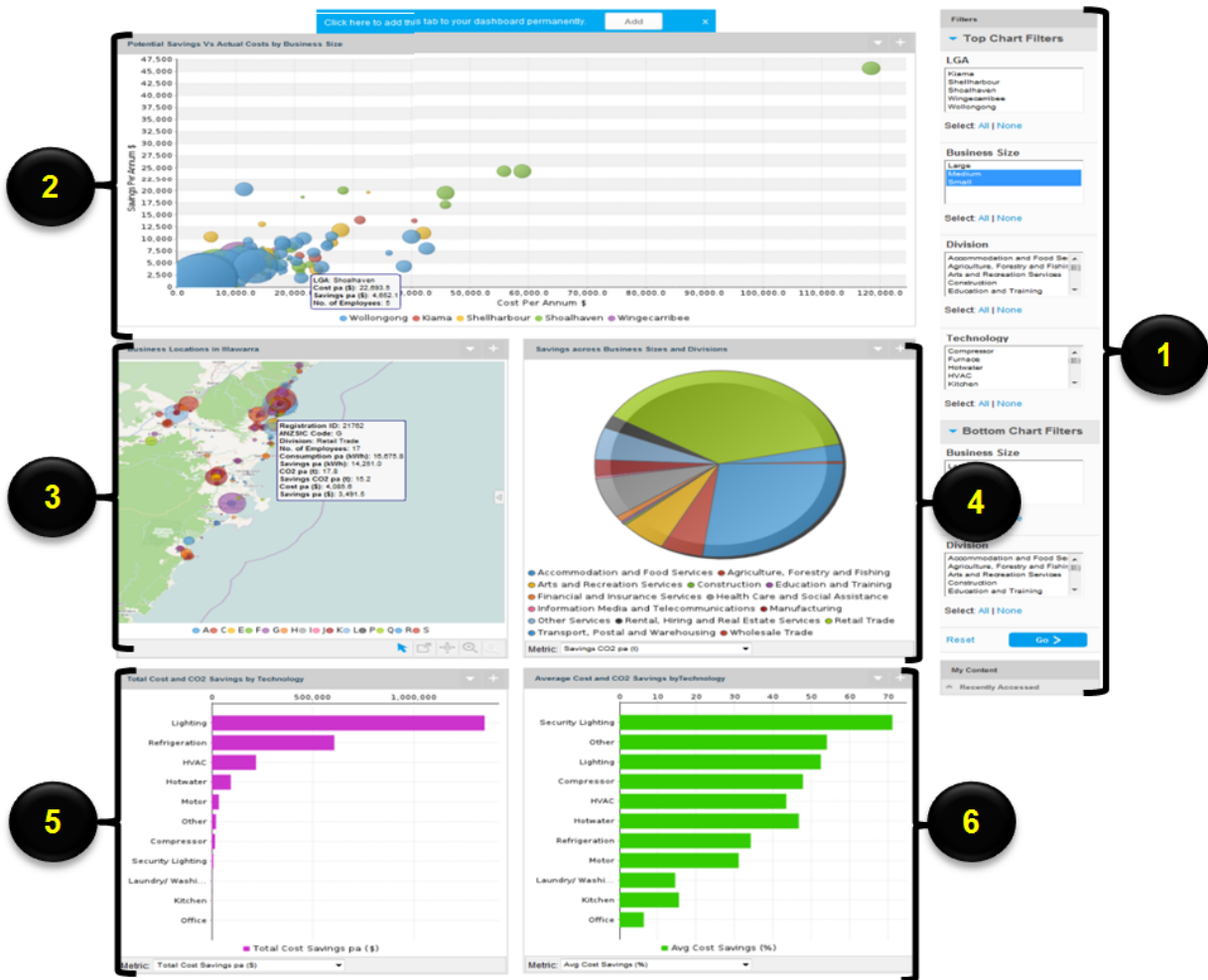
The importance of energy efficiency improvement has been a significant issue since the early 1970s<sup>4,5</sup>. The driving forces behind these programs include economic, social and environmental factors<sup>4</sup>. Communicating and educating the energy efficiency benefits to business users and decision makers is a critical part in ensuring SME community involvement in implementing government policies. The International Energy Agency (IEA) Scoreboard report for 2011 identified that some areas still require further development. Such areas are the availability of benchmarking information, incentives to make investment decisions and the need to design, improve and measure policies with specific focus on SMEs<sup>6</sup>.

SMEs invest substantial resources into the daily operation of their businesses<sup>7</sup>. Typically, SMEs lack the time and resources to invest in an energy efficiency project. Most SMEs consider such projects only when it can provide quick win and short payback period<sup>8</sup>. Many countries, including Australia, created energy saving policies and promoted energy efficiency programmers for SMEs. The challenge to policy makers is to reduce the information gap with minimum cost to SME<sup>9</sup>.

The NSW - Office of Environment and Heritage (NSW-OEH) has successfully implemented a business-focused energy efficiency program. This program helps SMEs reduce their energy costs and overcome many non-price barriers such as lack of capital and time. Those who invest in this program can cut energy cost without sacrificing service or quality, make significant contributions to a cleaner environment and improve their financial bottom line<sup>9</sup>. From state government's point of view, EED is an analytical web portal that enables assessing the effectiveness of OEH's energy efficiency program.

## **II. The Energy Efficiency Dashboard**

The SMART Infrastructure Facility at the University of Wollongong and the NSW-OEH have partnered to create an online analytical and reporting portal. This portal brings together information collected throughout the energy efficiency program in order to better inform business managers about the opportunities to improve their profitability and sustainability. The data portal (EED), shown in Figure 1, is designed to help SME overcome the information barrier and provide benchmarking information by presenting an effective, robust and highly interactive online analytical tool.



**Figure 1: The Energy Efficiency Dashboard (EED)**

To reduce the information gap, EED provides SME managers and decision makers in the Illawarra a benchmarking tool to understand how their business compare with other businesses from the same industry. EED focuses on presenting appropriate energy consumption and potential saving for SME in the Illawarra in a user-friendly fashion based on the user's defined role. EED turns the energy consumption data into knowledge that is easy to share with decision makers, policy makers and SME managers.

The dashboard includes identification of business-specific best energy saving appliances and practices, business types with high potential for saving energy and benchmarking energy use across business types. As a result, business users can evaluate and compare the effectiveness of their energy savings practices with other businesses in the same industry.

### **III. Study Area**

The study area corresponds to the Illawarra region (NSW, Australia). This coastal region, located south of Sydney, is made of five Local Government Areas (LGAs): Wollongong, Shellharbour, Kiama, Shoalhaven, and Wingecarribee.

### **IV. Data sets**

The data sets covered 1027 businesses with the majority located in the Wollongong area with 594 (57.8%) businesses followed by Shoalhaven 192 (18.7%), Shellharbour 121 (11.8%), Wingecarribee 74 (7.2%) and Kiama 46 (4.5%).

### **V. User Interface Design**

The EED is divided into the following six areas:

- 1) Filters: allow user to choose constraints that are relevant for their assessment, including LGA, Business Size (S/M/L), Technology and Division (according to the Australian and New Zealand Standard Industrial Classification - ANZSIC). Users can select one, more than one or all of these selections. It allow users to control all reports at once
- 2) Potential Savings Vs Actual Costs by Business Size: is a statistical bubble chart that shows the relationship between business electricity cost per annum and the potential savings. The color of a bubble indicates the LGA area whereas its size indicates the size of business based on the number of employees. Therefore, this bubble chart is an ideal tool to investigate the relationship of utility consumption and potential energy savings based on business size, location and industry.
- 3) Business location in the Illawarra: provides added value to users wishing to identify a business division and its potential saving. A SME manager is able to see all businesses clustered in the Illawarra region with individual total energy consumption and potential savings. From there s/he can drill into the equipments energy consumptions and its potentials savings level (see figure 2).

Table - Chart Representaion for Selected Business

OEH, 1/11/2012 11:47 AM

Technology	Savings pa (kWh)	Savings pa (\$)	CO2 Savings pa (t)	Division
Refrigeration	9,863.8	2,501.4	10.6	Retail Trade
Lighting	5,948.9	1,508.7	6.4	Retail Trade
Hotwater	838.8	212.8	0.9	Retail Trade

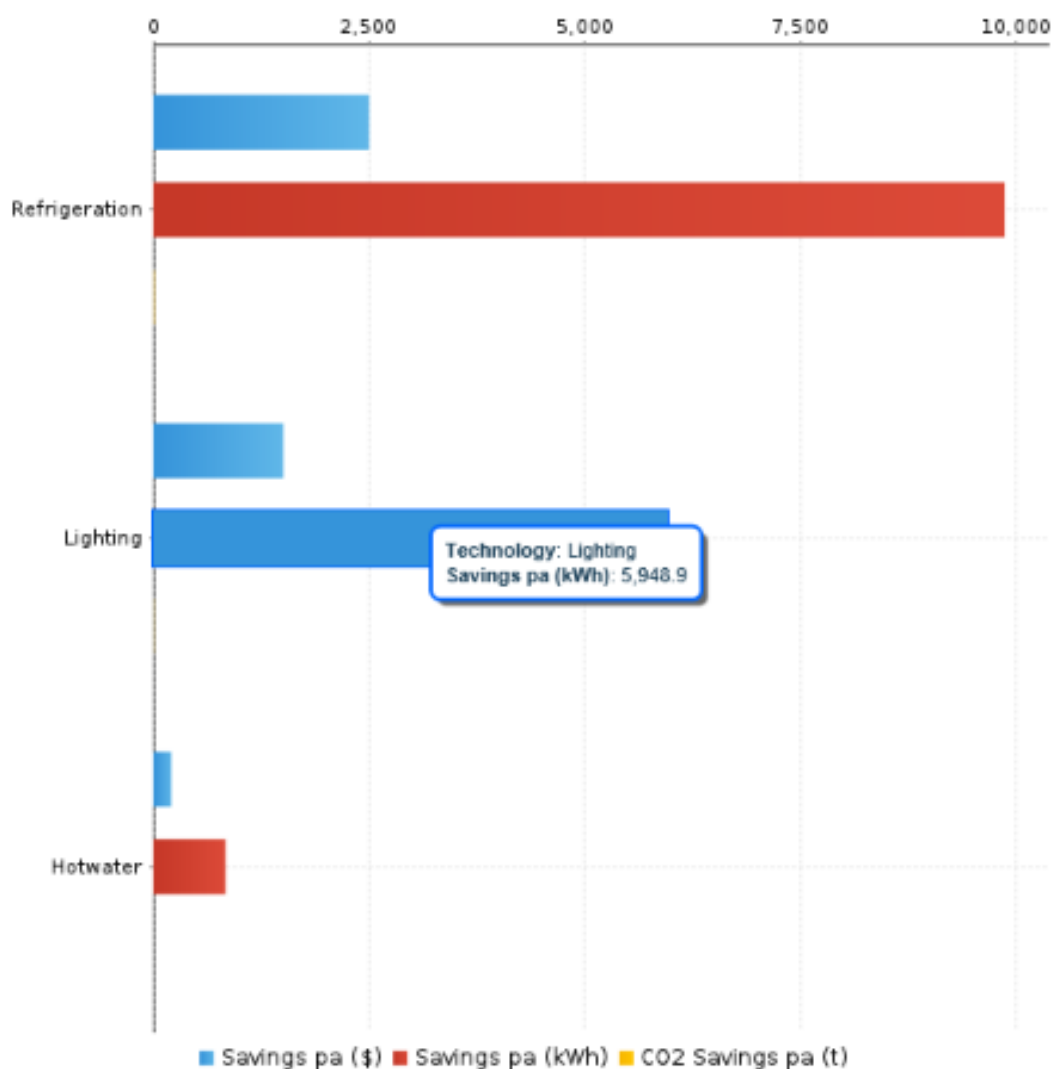
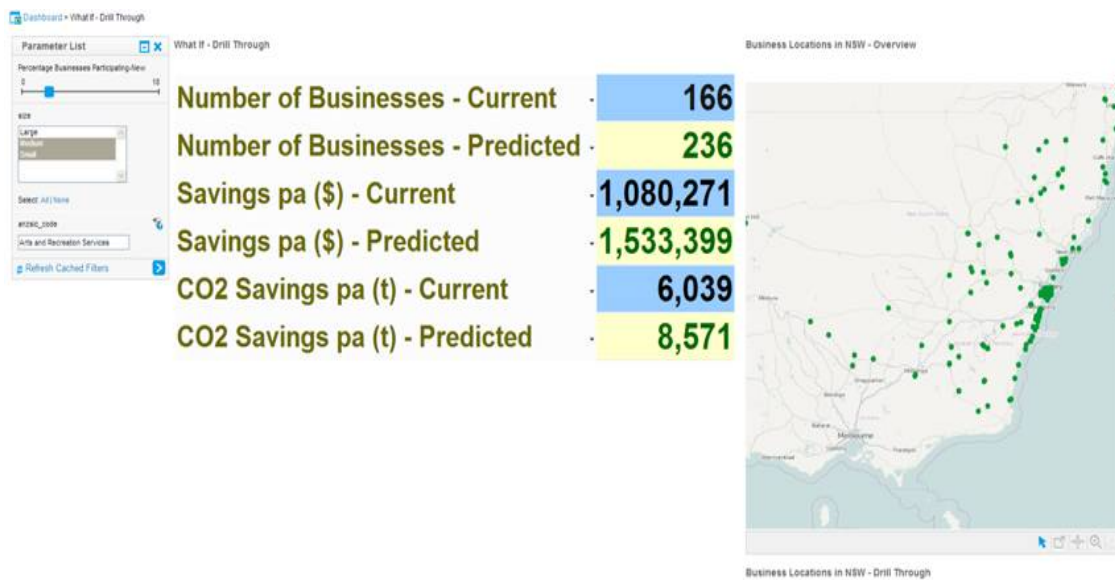


Figure 2: Equipment's potential energy saving



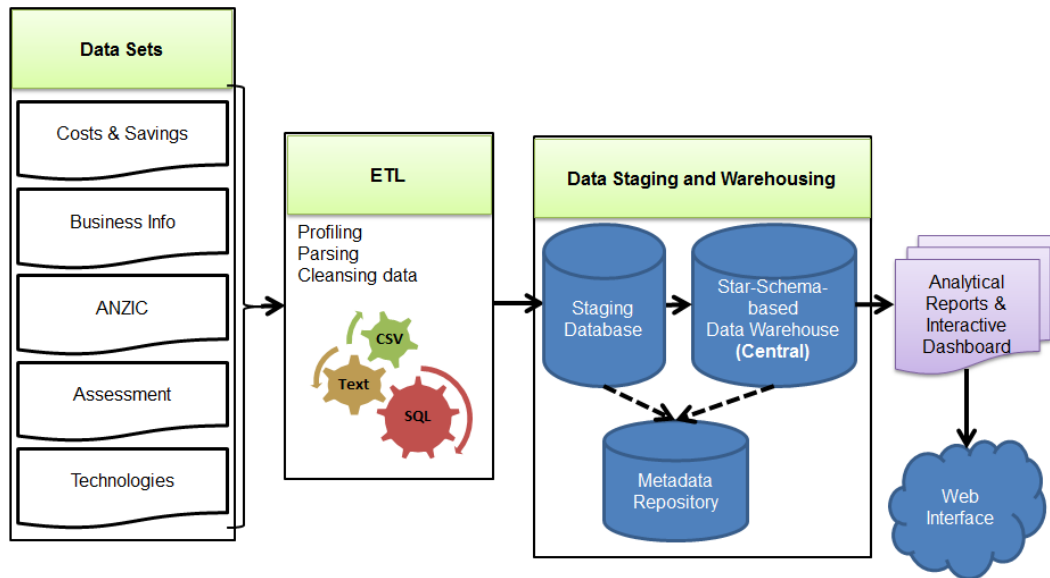
4) Savings across Business Size and Divisions: through this pie chart users can find the level of potential savings for each ANZSIC's division. This report also drills through to an integrated child report that enables "what-if" scenario analysis (see Figure 3). Using this integrated report, a user can estimate the expected utility consumption for a given industry under various scenarios, and compare the predicted value with the base case both in tabular form. For example, using a certain value for the population increase the user can see what efficiency gains would keep the expected usage within manageable limits. The usability and flexibility of this report is that it presents the user with a few easy-to-use sliders and filters to perform multiple scenario analyses on uptake of energy efficiency programme by SMEs.



**Figure 3: What-If Scenario Analysis**

5) Total cost and CO2 Savings by Technology: a bar graph that provides an overall view of potential savings pa in dollar value and tonne. The savings are presented in ascending order by equipment type such as HVAC, Refrigeration and Lighting.

6) Average Cost and CO2 Savings by Technology: this bar graph that provides an overall view of potential savings pa in dollar value and tonne. The savings are presented in an ascending order by equipment type.



**Figure 4: Technical Architecture and Workflows**

## VI. Technical Architecture and Workflows

We first describe the technical architecture and workflows involved in building the EED, and then how the users and policy makers could use this collection of tools. Figure 4 gives an overview of EDD and main workflows involved.

### 1. ETL

EED receives data from a number of providers in assorted file types and in heterogeneous structures. Extract, Transform and Load (ETL) is the standard process implemented to migrate such diverse data into an optimized data warehouse environment. This is applied in two stages process. In the first stage, data from disparate sources are extracted into a staging database where data cleaning, profiling and transforming operations take place. In the second stage, transformed data are loaded into a centralised star schema-based data warehouse.

### 2. Star Schema

The data warehouse is based on a Star Schema design. It maps data into one or more fact tables with multidimensional tables. A star schema can simplify data structure and provide capability to analyse data from multiple dimensions, thus enabling a user to perform various drill down, roll up and slice-and-dice views of data [8]. Coronel et al. (2013) provide an in-depth description of star schema and its variations used in data warehousing.

### 3. Analytical Reports & Interactive Dashboard

Reports & Dashboard use Web-based technologies to present energy efficiency information in a single view. These reports are built on top of the optimised star schema-based data warehouse. End users access this interactive content via an online portal with multiusers and multilevel access control. These access controls provide customised views of the data for different users.

## VII. Conclusion

The importance of energy efficiency improvement for SMEs has been a significant issue for several decades. Yet, there has been little action among SMEs to adapt their operations to enhance energy efficiency. NSW-OEH has successfully implemented a business-focused energy efficiency program, the purpose of which is to provide access to benchmarking information about the program and reduce the information gap. This program has the potential to highlight the opportunities available to SME managers to increase the energy efficiency of their businesses. EED is designed to provide such information for SME in the Illawarra.

The goals of EED go beyond providing energy efficiency and consumption related information for SMEs in the Illawarra; the portal targets stakeholders to communicate more effectively and provide benchmarking levels based on business categories. It is an easily scalable and flexible technology that can include an unlimited number of LGAs.

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# Cost-Driven Residential Energy Management for Adaption of Smart Grid and Local Power Generation

Weiliang Zhao<sup>a\*</sup>  
Paul Cooper<sup>a</sup>  
Pascal Perez<sup>b</sup>  
Lan Ding<sup>a</sup>

**Abstract:** A smart grid provides dynamic pricing signals which make users be possible to adjust their power demands accordingly. Renewable energy technologies equip a large number of residential homes the capability of local power generation. The varying price of power supply from a smart grid and the existence of local power generation bring opportunities and challenges for energy management at residential homes. This paper proposes a cost-driven residential energy management approach for the adaption of smart grid and local power generation. The target system makes cost-driven scheduling of household appliances by considering the real-time and/or predictable status of smart grid, local power generation, and power consumption demands. The proposed approach minimizes the overall daily electricity cost of household appliances by taking into account both weather and electricity tariff forecasts, predictable home activities, and the flexibility of electricity use.

**Key words:** Smart Grid; Dynamic Power Pricing; Renewable Energy; Power Demand Side Management.

## I. Introduction

Smart grids have become a promising means of the integrated management of electricity demand and supply. The smart grid is a convergence of information technology and communication technology for power system engineering by enabling utilities to make more efficient use of their existing assets through demand response, peak shaving, and service quality control<sup>1</sup>. A smart grid normally introduces variable electricity tariffs to reduce peak load across the network and thereby defers the need for investment in network augmentation<sup>2</sup>.

Smart homes utilize modern computer and communication technology in residential buildings to perform a variety of tasks with "ambient intelligence" with features that can benefit users for comfort, convenience, cost-reducing etc.<sup>3-4</sup>. Many residential homes have installed renewable

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<sup>a</sup> Sustainable Building Research Centre, University of Wollongong, NSW 2522, Australia

<sup>b</sup> SMART Infrastructure Facility, University of Wollongong, NSW 2522, Australia

\*Corresponding author: Weiliang Zhao [weiliang\\_zhao@uow.edu.au](mailto:weiliang_zhao@uow.edu.au)  
<http://dx.doi.org/10.14453/isngi2013.proc.53>

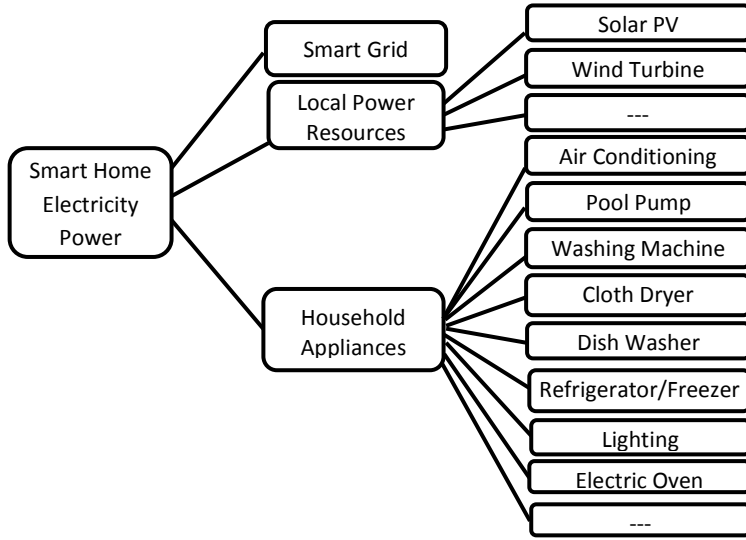
local power generation devices such as solar PV. The existence of local renewable energy sources<sup>5</sup> changes a residential home from a pure power buying party to a buying/selling party when it connects to the smart grid. The introduction of variable electricity tariffs from smart grids and bi-fold buying/selling role of a residential home bring the energy management tasks at residential homes new opportunities and challenges. In order to adapt the dynamic electricity tariffs of smart grids and equipped local power generation capability at residential homes, a cost-driven residential energy management approach is proposed. The target smart home system makes cost-driven scheduling by considering the real-time and/or predictable status of smart grid, local power generation, and power consumption demands. The proposed smart home system will support the automation of a residential home for the end-use of electricity from a smart grid with minimum electricity cost.

This paper describes a cost-driven energy management approach for adaption of smart grid and local power generation as an extension of our previous work<sup>6</sup>. The energy models and profiles of electricity facility and household appliances are refined and the genetic algorithm based solution is proposed. The target power smart home system is the central point to manage and control electricity consumption of household appliances and local power generation in the context of smart grid. The approach aims to minimize the cost of a residential home by taking account of home occupants' activity plans, weather conditions, local renewable energy generation, varying price of power supply from a smart grid, and the flexible and inflexible electricity consumptions of household appliances.

This paper is organised as follow. Section 2 describes energy models and profiles of electricity facility and household appliances at residential homes. Section 3 reviews our previous work which formalizes the scheduling of electricity consumption and local generation at residential homes as an optimization problem. Section 4 presents the genetic algorithm based solution of the identified optimization problem. Section 5 provides a conclusion for the paper.

## **II. Energy Models and Profiles of Electric Facility and Household Appliances**

Bonino and colleagues have proposed a semantic energy information publishing framework<sup>7</sup>. This framework is lacking of the capability to express the electricity consumption details in the context of weather conditions and occupant activities. This section describes our energy models for the smart grid, local power resources, and individual household appliances, which are the foundation for electrical energy information to be collected, organized, searched, and utilized. The category of electricity facility and household appliances in a residential house is as in Figure 1.



**Figure 1. Electric Facility and Household Appliances.**

Each element in the above category has its energy model and will be implemented with a specific data structure in database or profile document. The consumption status of an individual device is considered under conditions as day\_type, occupants\_activities\_plan, and weather. The day\_type may have values as “week\_days”, “week\_ends”, or “public\_holidays”. The occupants\_activity\_plan may have values as “week\_day”, “week\_end”, “home\_holiday”, and “home\_away\_holidays”. The weather may include month, temperature, wind, and sunshine\_status. The home occupants’ activities plan may include energy consumption related activities and people number at home. Due to the paper length limit, we will not provide all details for possible values of these conditions. As an example, the sunshine\_status may have the value as “sunny”, “mostly\_sunny”, “cloudy”, or “raining”.

Here we provide the generic descriptions of the energy models for electricity facility and household appliances. Most of these data may be collected by the installed ZigBee Panel Meter<sup>8</sup> with time interval of 15 minutes.

- **Smart Grid** has data fields “time\_point, tariff, current, voltage, power\_consumption, day\_type, weather”.
- **Solar PV** has data fields “time point, current, voltage, power\_generation, weather”.
- **Air Conditioning** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption, temperature\_setpoint, day\_type, occupants\_activities\_plan, weather”.
- **Swimming Pool Pump** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption”.
- **Washing Machine** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption”.
- **Cloth Drier** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption”.

- **Dishwasher** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption”.
- **Refrigerator/freezer** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption, day\_type, occupants\_activities\_plan, weather”.
- **Lighting** has data fields “appliance\_id, time\_point, current, voltage, power\_consumption, day\_type, occupants\_activities\_plan, weather”.
- **Electrical Oven** has data fields “appliance\_id, time\_point, on\_off, mode, current, voltage, power\_consumption, day\_type, occupants\_activities\_plan”.
- **Other Devices** has data fields “appliance\_id, time\_point, current, voltage, power\_consumption” (day\_type, occupants\_activities\_plan, weather may be included).

Energy profiles will be built up based on the above data structures. These energy profiles will be the foundation of the energy analysis and decision support systems for smart electrical energy management at residential homes. The original data of energy profiles could be obtained and updated with the help of smart meters, home sensors, home activity records, weather station reports, power facility providers etc. Due to the page limit of the paper, here we simply assume they are available and will not provide more details of how to establish and update them.

### III. Cost-driven Demand Optimization in the Context of Smart Grid and local Power Generation

This section presents an overview of our previous work that formalizes the scheduling of electricity consumption and local generation at residential homes as an optimization problem.

#### IV. Power Price Model

Smart grids normally have variable electricity tariffs. With local power generation, a residential home will buy/sell power from/to a smart grid. The power price model is crucial in the cost-driven demand optimization in the context of smart grid and local power generation. At residential homes, the supply of electrical power is composed of two parts which will be referred to as local-power and grid-power. The voltage of a smart grid at time  $t$  is denoted as  $V_{grid}(t)$ . It is assumed that electrical power cannot be sent to the smart grid if  $V_{grid}(t)$  is equal to or higher than a threshold value  $V_{threshold}$ . In the following part of the paper, the variable  $V_{gap}(t) = V_{threshold} - V_{grid}(t)$  will be used for judging the real time situation. From the point of view of smart grid customers, one of the major features of a smart grid is its time-variable pricing. The local power generation at residential homes must integrate with the smart grid. The power price model is critical in the successful business operation of a smart grid. Considering the characteristics of smart grids, the following price model is adopted:

The grid-power has a variable tariff  $T_{grid}(t)$  which is determined by the smart grid.

- If  $V_{gap}(t) > 0$ , the selling price of a local power to the smart grid is  $T_{local}(t) = T_{grid}(t) - \Delta$ . The  $\Delta$  is a constant value.
- If  $V_{gap}(t) \leq 0$ , a local power cannot be sold to the smart grid.

#### V. Demand Optimisation

There are  $n$  household appliances with power consumption rate  $U_1, U_2, \dots, U_n$  and  $m$  local power resources with power generation rate  $R_1, R_2, \dots, R_m$ . The  $U_i$  ( $i=0, \dots, n$ ) has variables denoted by a vector  $\mathbf{x}_i$ . These variables reflect the flexibilities of power consumption of household appliances. The  $R_i$  ( $i=0, \dots, m$ ) has variables denoted by a vector  $\mathbf{y}_i$ . These variables reflect the flexibilities of power generation of local power sources. An example of variables is the starting time of an electric facility. Referred to energy models and profiles for individual electrical entities described previously,  $U_i(\mathbf{x}_i, t)$  ( $i = 1, \dots, n$ ) and  $R_i(\mathbf{y}_i, t)$  ( $i = 1, \dots, m$ ) are built up in a specific set of day type, occupants activities plan, and weather forecast.

With  $X$  to represent  $[\mathbf{x}_i (i = 1, \dots, n)]$  and  $Y$  to represent  $[\mathbf{y}_i (i = 1, \dots, m)]$ , the net electrical consumption rate at a specific time point  $t$  is

$$P(X, Y, t) = \sum_{i=1}^n U_i(\mathbf{x}_i, t) - \sum_{i=1}^m R_i(\mathbf{y}_i, t)$$

Please, note that the above net electrical consumption rate  $P(t)$  could be either positive and negative. The negative value means that the residential home generates more electrical power than what it is consuming at time  $t$ . The residential home may buy from or sell to the smart grid electrical power. The net cost rate of the residential home is:

$$\begin{aligned} & \text{If } P(X, Y, t) \leq 0, \quad C(X, Y, t) = 0; \\ & \text{if } P(X, Y, t) > 0, C(X, Y, t) = P(X, Y, t) \times T_{\text{grid}}(t); \\ & \text{if } P(X, Y, t) < 0 \\ & \quad \text{if } V_{\text{gap}}(t) \leq 0, C(X, Y, t) = 0 \\ & \quad \text{if } V_{\text{gap}}(t) > 0, C(X, Y, t) = P(X, Y, t) \times T_{\text{local}}(t) \end{aligned}$$

In the proposed approach for electrical energy management, a specific time period  $T$  is considered in the prediction, recommendation, and schedule of electrical consumption and local generation. A practical period could be a whole day as 24 hours from 8:00 AM to the following day's 8:00 AM. The specific time period  $T$  is divided into  $N$  time intervals. An individual time interval is  $\Delta T = T/N$ . The total cost of the residential home in time period  $T$  is:

$$C_{\text{total}}(X, Y) = \sum_{t=0}^N C(X, Y, t) \times \Delta T$$

The schedules of electrical consumption and local generation at a residential home becomes the optimization problem for minimizing the total cost of electrical power while satisfying power requirements at a residential home.

#### IV. Genetic Algorithm based Solution of Identified Optimization Problem

The optimization problem is a typical nonlinear problem that conditional judgments based on dynamic variables are embedded in the cost calculation. In the identified optimization problem, there are multiple variables to be optimized. The method of the whole variable space searching calculates costs for all possible ways and compares them to get the minimum. When the number of variables to be optimized is too big, the whole variable space searching will become impossible. The previous work<sup>6</sup> has provided an approximate solution of the identified optimization problem based on first principles. The correlations among consumption demands of household appliances have not been considered. It is necessary to find a robust and powerful solution which can cover a wide range of situations in the identified optimization problem.



The genetic algorithm proposed by Holland<sup>9</sup> provides a robust and efficient optimization solution to cost-driven scheduling. The optimization procedure of a genetic algorithm generally includes four main steps: selection, crossover, mutation and evaluation. Using a biological metaphor, the optimization procedure successively uses ‘gene’ selection, crossover and mutation operations, before performing a recursive fitness evaluation until final convergence.

In this project, we choose Python as the programming language and the Pygene package<sup>10</sup> to perform the computing tasks. Pygene is a simple and easily understandable library with a rich set of primitive classes for genetic algorithms and genetic programming in python. The development platform is Intel(R) Core™ i7-2640 CPU @ 2.80GHz 2.80 GHz with 8.00 GB RAM. The Python version is 2.7.3 under an Integrated Development Environment JetBrains PyCharm 2.6.1.

In the implementation, classes FloatGeneMax, MendelOrganism, and Population in pygene packages are employed as the major working horses. The fitness function implements the total cost of the residential home in a specific scheduling time period which is the whole 24-hour day from 4:00 AM of next day to 4:00 AM of the day after next day. The individual time interval is 15 minutes. The calculation follows the formula in section 3.2. A set of genes represent the variables described in section 3.2 which reflect the flexibilities of power consumption of household appliances and power generation of local power sources. The constraints are that all the power consumption tasks of household appliances and power generation tasks of local power sources must be completed in the scheduling time period. In our implementation of FloatGeneMax, both the crossover parameter and the mutation parameter are 0.5. We have achieved stable computing results for variable numbers from 1 to 10.

As a comparison, we have tried to use the method of whole space searching to solve the optimization of total cost. The computing time of whole space searching will increase exponentially when the number of variables becomes bigger. When the number of variables is bigger than 3, the whole space searching becomes impossible. Comparing with the approximate solution by Zhao et al.<sup>6</sup>, the genetic algorithm provides more accurate optimization results.

## V. Conclusion

This paper reports our work-in-progress result of proposed approach to minimize the overall daily electricity cost of household appliances by taking into account weather and electricity tariff forecasts, predictable home activities, and the flexibility of electricity use. The energy models and profiles of electric facility and household appliances have been described. The cost-driven scheduling of power consumption and generation has been identified as an optimization problem. A genetic algorithm based solution has been developed to achieve more accurate optimization results comparing with previous work that has not considered the correlations among consumption demands of household appliances.

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# Effective Water Management in the Mahaweli Reservoir System; Analyzing the Inflow of the Upmost Reservoir

W. M. N. Dilini<sup>a</sup>  
Liwan Lyanage-Hansen<sup>b</sup>  
M.T.D. Attygalle<sup>a</sup>  
K. D. W. Nandalal<sup>c</sup>

**Abstract:** Mahaweli cascaded reservoir system is built contiguous to the Mahaweli river, enhancing the water storage and transferring ability to reinforce the needs of water in accordance with the climatic changes. The foremost requirement of the system is to provide water for irrigation and to produce hydroelectricity to the country that has given rise to conflicting demands of water requirements from the two sectors. Forecasting future water availability is crucial to predict the hydroelectricity generation capacity while maintaining a balance between the provisions of water to both sectors. Therefore, modeling the changes of in-flow of the upmost reservoir is substantial to effective water management. Literature has not revealed much evidence for an existence of an accepted statistical model in predicting the inflow, of the system considered. This research is based on the methodologies to test for the seasonality, stochasticity and non-linearity of the in-flow, in advance to fitting a suitable model.

**Key words:** In-flow; Stochasticity; Non linearity; Seasonality.

## I. Introduction

Hydroelectricity is the production of electrical power through the use of the gravitational force of falling or flowing water. As with most other countries, in Sri Lanka too, hydroelectricity is one of the main sources to cater to the increasing demand of electricity. Mahaweli hydropower system which originated under the Mahaweli Ganga Development Programme, is the largest integrated rural development multi-purpose programme based on water resources of Mahaweli and allied six river basins. The foremost requirement of the system is to provide water for irrigation and to produce hydroelectricity to the country that has given rise to conflicting demands of water needs mainly from the two sectors power generation and agriculture.

Mahaweli hydro power complex consists of six major power stations which had an installed capacity of 660 MW. Currently, it contributes to around 13% electrical energy to the country

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<sup>a</sup> Department of Statistics, University of Colombo, Colombo 03, Sri Lanka.

<sup>b</sup> School of Computing and Mathematics, University of Western Sydney, Australia.

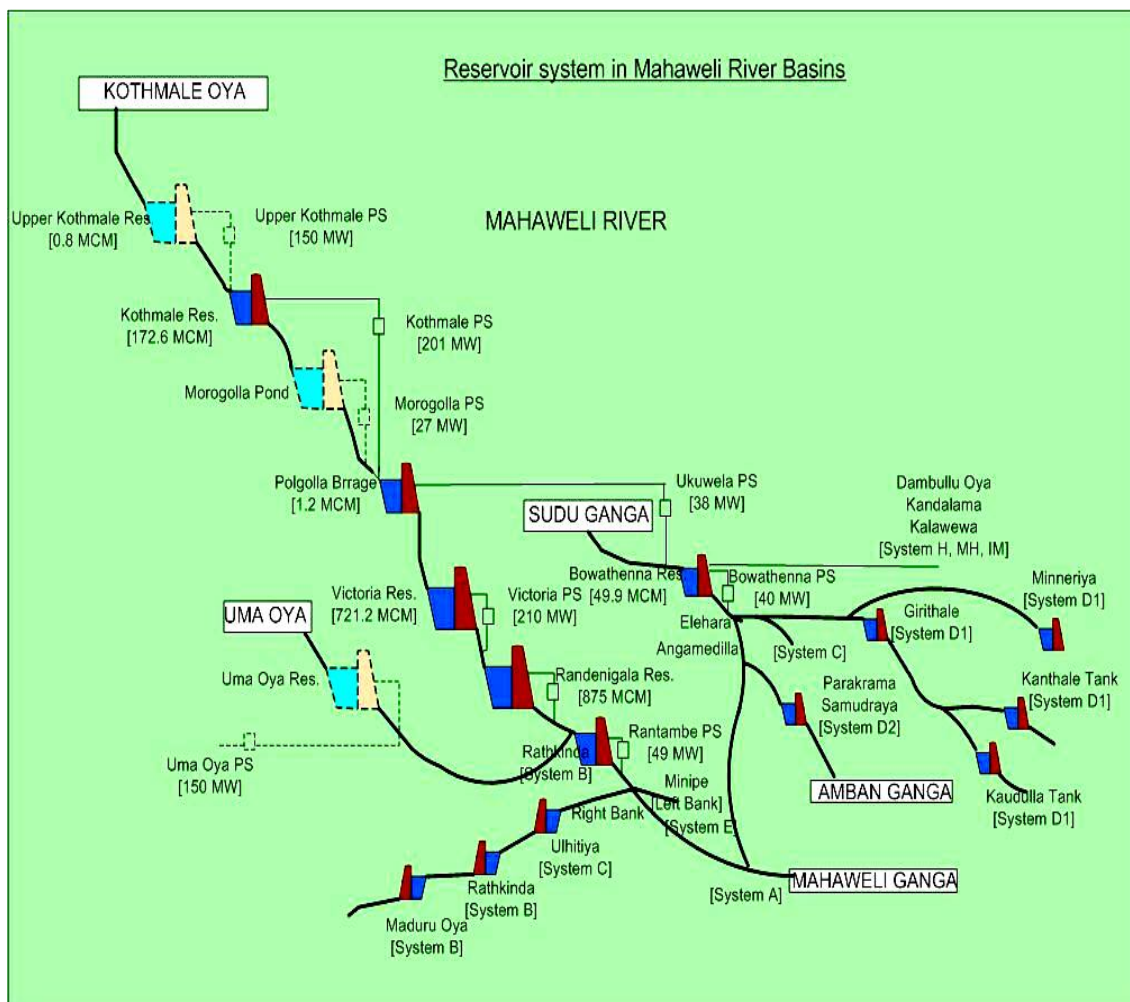
<sup>c</sup> Department of Civil Engineering, University of Peradeniya, Peradeniya, Sri Lanka.

\*Corresponding author: Liwan Lyanage-Hansen [llyanage@uws.edu.au](mailto:llyanage@uws.edu.au)

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annually. The major power stations coming under Mahaweli complex are, Kotmale, Victoria, Randenigala, Rantambe, Ukuwela, Bowatenna and Nilambe covering 1268 sqkm of Mahaweli basin. This research is carried out based on these five reservoirs starting from Kotmale flowing down the line.

Hydroelectricity is the production of electrical power through the use of the gravitational force of falling or flowing water. As with most other countries, in Sri Lanka too, hydroelectricity is one of the main sources to cater to the increasing demand of electricity. Mahaweli hydropower system which originated under the Mahaweli Ganga Development Programme, is the largest integrated rural development multi-purpose programme based on water resources of Mahaweli and allied six river basins. The foremost requirement of the system is to provide water for irrigation and to produce hydroelectricity to the country that has given rise to conflicting demands of water needs mainly from the two sectors power generation and agriculture.



**Figure 1.** Schematic diagram for the cascaded reservoir system in Mahaweli river basins.

Mahaweli hydro power complex consists of six major power stations which had an installed capacity of 660 MW. Currently, it contributes to around 13% electrical energy to the country annually. The major power stations coming under Mahaweli complex are, Kotmale, Victoria, Randenigala, Rantambe, Ukuwela, Bowatenna and Nilambe covering 1268 sqkm of Mahaweli basin. This research is carried out based on these five reservoirs starting from Kothmale flowing down the line.

In Sri Lankan context, accurate prediction of the generation of the hydroelectricity from the Mahaweli system is of vital importance to determine the ability of satisfying the future electricity needs and to minimize the wastage of resources due to inaccurate predictions. Forecasting the hydroelectric generation, however, requires a comprehensive knowledge of future availability of water resources.

Modeling the in-flow to the upmost reservoir Kothmale is substantial in that regard, as the whole system depends upon the changes in the natural behavior of this in-flow. Thus a better understanding of the natural inflow is of utmost importance. Original data for the in-flow are recorded on a daily basis and these were initially aggregated to weekly, monthly and annually by calculating the averages. The data set consists of daily data values from 1997 to 2011 which includes 14 years of data altogether. The number of observations for the Kothmale reservoir is 5478 and those were recorded as 365 per each year with the exception of leap years.

This paper presents the analysis of the basic characteristics of the hydrological process for the upmost natural in-flow in order to understand the stream-flow process using univariate time series.

## **II. Related Literature**

The focus of the analysis is based on the stochasticity, stationarity and linearity of the in-flow data. The Literature related to analyzing these characteristics of the in-flow was explored and the techniques found were implemented.

### **A. Stochasticity**

A stochastic process is a statistical process involving a number of random variables depending on a variable parameter. If the variable parameter is the time, then the process becomes a stochastic time series in this analysis the in-flow series. The most important aspect of the stochasticity is stationarity. A series  $\{X_t\}$  is called stationary if its statistical properties do not change with time. More precisely,  $\{X_t\}$  is said to be completely stationary if, for any integer  $k$ , the joint probability distribution of  $x_t, x_{t+1}, \dots, x_{t+k}$  is independent on the time index  $t$ . There can be two types of stationarity tests, namely the trend test and the unit root test. The first test is done to determine if the values of a series have a general increase or decrease with the time increase while the latter test is done to determine if the distribution of a series is dependent on the parameter 'time'.

The Mann–Kendall trend test is one of the widely used non-parametric tests to detect significant trends in time series. This test, being a function of the ranks of the observations rather than their actual values, is not affected by the actual distribution of the data and is less sensitive

to outliers. On the other hand, parametric trend tests, although more powerful, require the data to be normally distributed and are more sensitive to outliers. The Mann–Kendall test is therefore more suitable for detecting trends in hydrological time series, which are usually skewed and may be contaminated with outliers. This test has been extensively used with environmental time series<sup>1</sup>.

### **B. Seasonal Unit Roots**

Most of the time series data are evident of substantial seasonal fluctuations rather than the usual trend. The trend of time series data can be addressed by the so called Augmented Dickey-Fuller (ADF) test in order to identify the fulfillment of stationary assumptions. If seasonality is present in time series data, there are no such tests in common practice and hence most of the researchers have overcome this issue simply by using seasonally adjusted data.

The seasonal adjustment can lead to destroy important relationships between economic time series data<sup>2</sup>. Since the seasonal component is not only present in the economic time series data but also severely occurring in environmental data, a testing procedure should be there to identify the seasonal fluctuations in time series data without removing the seasonality. There are many tests that are proposed for testing seasonal unit root tests such as Dickey-Hasza-Fuller (DHF) test<sup>3</sup>, OCSB test<sup>4</sup>. Among these seasonal unit root tests the HEGY test<sup>5</sup> has the advantage of testing seasonal unit root at each frequency separately<sup>6</sup>. According to the work carried out by Emparanza<sup>7</sup> the methods introduced by Hylleberg et al.,<sup>6</sup> were generalized in a way that p-values for any periodicity can be calculated.

### **C. Non-Linearity**

Stream flow processes are commonly perceived as nonlinear. They could be governed by various non linear mechanisms acting on different temporal and spatial scales<sup>8</sup>. He further elaborates that the BDS test is a non parametric method for testing for serial independence and non linear structure in a time series based on the correlation integral of the series.

### **D. Seasonality and Spectral Analysis**

The dynamics of stream flow are often dominated by annual variations. How well the seasonality is captured is very important criterion for assessing a stochastic model for streamflow<sup>8</sup>. Out of the cycle plots<sup>9</sup> to study the behavior of seasonal time series, seasonal subseries plots is a cycle plot that can be effectively used in detecting seasonality in a time series. However, this plot is only useful if the period of the seasonality is known in advance. A spectral plot is a graphical technique for examining cyclic structure in the frequency domain. Uneven long term variations in the series, other than trend, are called cycles. Spectral analysis is a statistical approach to detect regular cyclical pattern, or periodicities. In Spectral Analysis the data are transformed with a finite Fourier transformation and decomposed into waves of different frequencies. Thus the time series data are expressed in terms of sine and cosine components.

## **III. Analysis**

According to Figure 2 (left), annual average inflow shows fluctuations between the range from 1.6 mcm to 2.5 mcm with the exception of 3.36 mcm for the year 2010. The yearly data

series according to Figure 2 (right) for monthly data, seasonality can be seen but the length of periodicity of the seasonality is not very clear. The data seem to be not having significant trends and they seem to be somewhat stationary.

### E. Testing for Stochasticity

In order to detect the nature of stochasticity, the stationarity of the in-flow series is observed. Testing for the trend in the in-flow time series, in other words, determining whether the values of a series increase or decrease with time, is presented in Table 1.

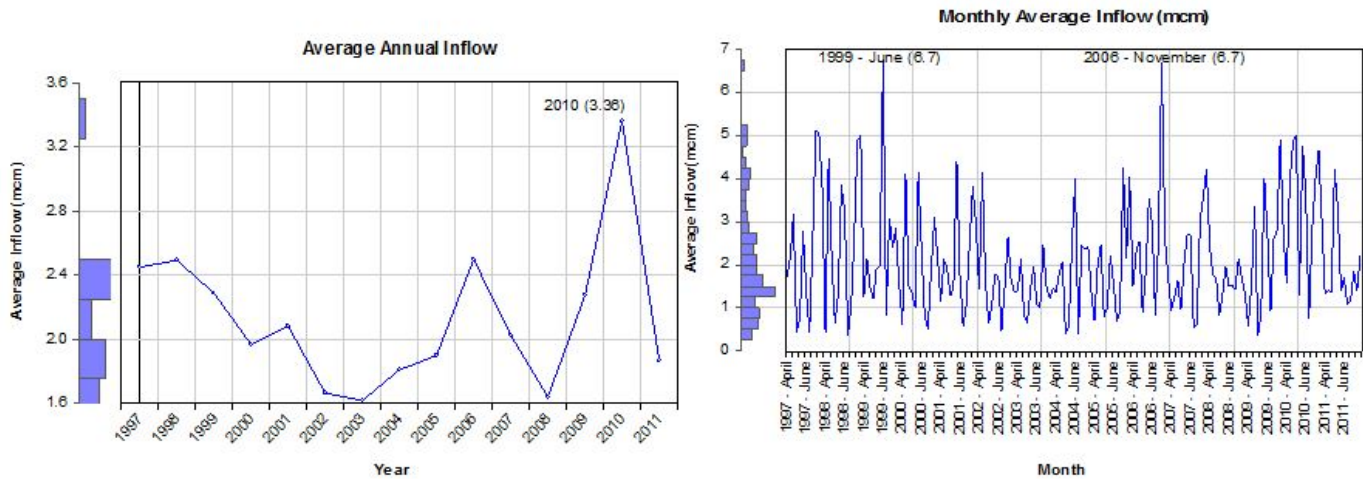


Figure 2. Magnetization as a function of applied field.

Table 1: Mann Kendall Trend Test results for monthly inflow series of year 1997 – 2011.

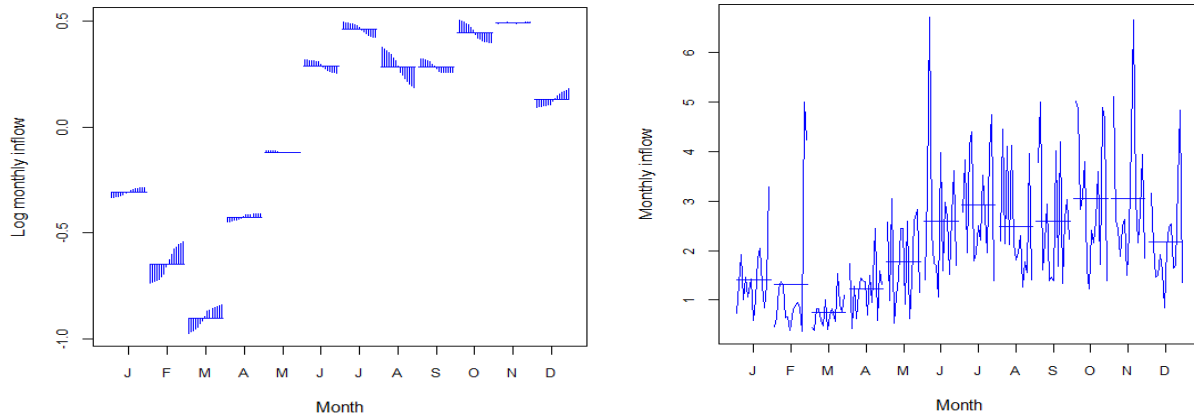
Month	Score	Tau	2-sided p value	Month	Score	Tau	2-sided p value
January	17	0.162	0.42848	July	-4	-0.0383	0.88183
February	22	0.211	0.29811	August	-48	-0.459	0.019872
March	40	0.383	0.053314	September	-8	-0.0766	0.72872
April	13	0.124	0.55262	October	-21	-0.2	0.3223
May	10	0.0957	0.65565	November	-1	-0.00952	1
June	-2	-0.0191	0.96048	December	15	0.143	0.48842

Observing the results, it can be concluded that, only the month August can be detected to be having a trend in the inflow series at 5% level of significance. The lack of having monthly trends in the series can be accepted to a certain extent as environmental data must be having more seasonality than trends.

### F. Testing for Seasonality

The seasonality in the inflow series was observed on a monthly basis since monthly flows usually exhibit strong seasonality according to Literature. The graphical technique “seasonal sub series plot” was used for this purpose.

Seasonal sub series plot for monthly data was initially plotted (left) and the same plot for log series was also obtained (right) due to the higher variability in the raw monthly series. The second plot reveals a seasonality pattern. The inflow series shows a peak in November whereas July and October also shows a value very close to that. The inflow series exhibits very low occurrence for the months of February and March. Starting from March, inflow series steadily increase until July and then show up a slow decrease until October. Then, the series again rises in the November and decreases until March.



**Figure 3. Seasonal sub series plots for monthly data from year 1997 - 2011**

The inflow series heavily depend on the rainfall patterns and river flow patterns. The rainfall also acts as one of the factors that affect the river flow pattern. Paddy cultivation in Sri Lanka is being done for two main seasons “yala”(October - March) and “Maha”(April – September) considering the rainfall variation. The inflow series exhibit a pattern somewhat close to this grouping which suggests incorporating the seasonality in the rainfall to predict the inflow for further studies.

### G. Testing for Stationarity

As seasonal decomposition may lead to loss of important information, stationarity (existence of seasonal unit roots) was tested in the presence of seasonality using the HEGY procedure (Table 2).

**Table 2: HEGY test results for monthly data from year 1997 – 2011.**

Deterministic: constant + (s-1) seasonal dummies + trend					N.Obs=167, lag-order=1		
Statistic	t1= 2.82	t2= 2.97	F1= 12.22	F2= 17.63	F3= 11.21	F4= 12.12	F5= 8.28
p-value	0.0423	0.0239	0.0003	0.0000	0.0007	0.0003	0.008
Ang. Frequency	zero	$\pi$	$\mp \pi/6$	$\mp \pi/3$	$\mp \pi/2$	$\mp 2\pi/3$	$\mp 5\pi/6$

Calculated p-values for all seasonal unit roots (monthly) are less than 0.05. Thus, there is enough evidence to reject the null hypothesis of the existence of a unit root. Therefore it can be



concluded that the monthly series of inflow does not have seasonal unit roots that suggests stationarity. The same procedure for weekly data also provided evidence at 10% level of significance that the series does not have seasonal unit roots.

### H. Testing for Non-Linearity

BDS test for linearity/non-linearity assumes that the series of interest is stationary. Since the monthly series and weekly series gave up satisfactory results BDS test can be applied here to check for non-linearity (Table 3).

**Table 3: BDS test results of the inflow series from 1997 – 2011 for four time scales**

Time Scale	Dimension = 2		Dimension = 3		Dimension = 4		Dimension = 5		Dimension = 6	
	Statistics	p value	Statistic	p value	Statistic	p value	Statistic	p value	Statistic	p value
Daily	0.08484	0	0.14454	0	0.181594	0	0.200795	0	0.20717	0
Weekly	0.07124	0	0.109348	0	0.132478	0	0.144014	0	0.14674	0
Monthl	0.01369	0.0191	0.013696	0.0064	0.032379	0.0035	0.036281	0.0017	0.03628	0.0009
Annual	0.00120	0.9604	-	0.0081	-	0.2851	-	0.1811	0.01396	0.8014

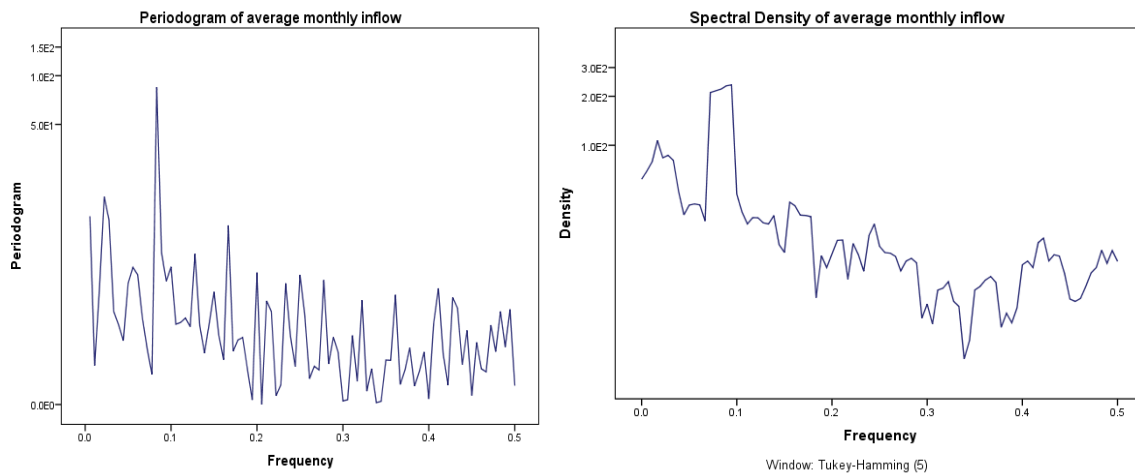
The test statistic for BDS test as indicated above, decreases with the increase of time scale, from daily to annual. Therefore, it can be stated that non linearity decreases with the increase in time scale. Further considering the p-values, it can be concluded that the strongest non-linearity is viewed for the daily series. Weekly and monthly series are also non linear at 5% level of significance. However, it can also be concluded that the annual series is linear as it's p-value is 0.96. This result is in agreement with the statement 'All annual series are linear'<sup>10</sup>. However, the seasonality in the inflow series is assumed to be annual in the previous analyses and it might not be the actual case for in-flow data.

### I. Spectral Analysis

Initially, the monthly series was tested to verify the existence of an annual periodic component as tested above. The above seasonality test is carried out assuming that data contain annual periodic components. The validity of this assumption was checked using the periodogram drawn for monthly data. An annual periodicity corresponds to a period of 12 as the inflow series with this data are monthly values. Since the period and frequency are reciprocals of each other,

period of 12 corresponds to a frequency of  $1/12$  ( $\approx 0.083$ ). When analyzing the periodogram, it can be seen that the highest peak is at frequency 0.083.

Spectral density function, which is a smooth version of the periodogram is analyzed for the remaining peaks. Although the density plot consists with distinct peaks, starting from the lowest frequency peak for the period 12, those peaks are not equally spaced. Thus, the existence of annual periodic components cannot be confirmed.



**Figure 4: Periodogram (left) and Spectral Density (right) graphs. Period: 1997 - 2011**

#### IV. Future Work

The major advantage of Artificial Intelligence modeling is the considerable ability to map input-output pattern without requiring prior knowledge about the factors that affect the forecasting parameters, and have forecasted daily levels using adaptive network-based fuzzy inference system<sup>11</sup>. In order to handle the random nature of the problem, the literature suggests that neural networking could be a supporting methodology to deal with such complex problems.

Another set of researchers on the other hand state that natural processes are complex, and it is sometimes not possible to build a single global model that adequately captures the system behaviour<sup>12</sup>. They claim that the training data can be split into a number of subsets, and separate specialized models can be built on each subset. These models are called local or expert models, and sometimes called as a committee machine. Thus, a combination of several methodologies, such as time series analysis and neural networking may resolve and find a reasonable solution to the problem of this study.

#### Conclusion

The inflow series does not consist with monthly trends and seasonal unit roots at frequencies monthly and weekly. The reason to these results may due to the absence of annual periodicity which was detected through spectral analysis. High dependency of the series with the rainfall

patterns and river flow patterns can be visualized through the monthly seasonal patterns of the data. Non linearity of the series decreases with the increase in time scale. The analysis concludes confirming the chaotic and volatile nature of inflow series, which need to be catered through data driven methodologies described in section 4.

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## **Coping with new challenges in water resources management in Bangladesh**

Md.Shahadat Hossain<sup>a\*</sup>  
Musfiquir Rahman<sup>a</sup>  
Mir.Md.Tamim<sup>b</sup>

**Abstract:** One of the most stressed resources in Bangladesh is water. Major challenges facing sustainable water resources management in the country today include: increasing vulnerability to extreme events, unrestricted extractions, growing urban demand, climate change, land-use changes and environmental requirements. In this context, the study gives an overview of existing water management practices in the country; and elucidates the role of hydrological services including focused Research and development (R&D) in resolving water resources issues. A recent effort in enhancing institutional capacity for decision making is elaborated in the context of implementation of various Hydrology Projects. R&D efforts in water sector are shown to embrace two major roles in furthering sustainable water resources management: i) helping to decrease the vulnerability by furthering development and increasing adaptive capacity, and ii) giving an option to respond to numerous contingencies that an unknown future holds.

**Key words:** Water resources problems; WR engineering; Hydrology of Bangladesh.

### **I. Introduction**

At the beginning of 20<sup>th</sup> century, the population of Bangladesh was approximately 3 crore; which rose to 14 crore at the beginning of 21<sup>st</sup> century, and to about 16 crore today. With the growth of human population has come the increased need for resources to sustain the multitude. Food and water are two of the basic human needs; and the latter, in the form of irrigation, is necessary to produce much of the former. As world population increases, a catastrophe as predicted by many thinkers may or may not befall on the human race, but one thing is certain: what we get would be increasingly difficult choices, especially as regards water resources management, which can only be dealt effectively by the best available technology. Modern

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<sup>a</sup> Institute of Water Modelling (IWM), New DOHS, Mohakhali, Dhaka-1206, Bangladesh

<sup>b</sup> Department of Civil Engineering, Southern University Bangladesh, Mehediagh Road, Chittagong, Bangladesh

\*Corresponding author: Md.Shahadat Hossain [shn@iwmbd.org](mailto:shn@iwmbd.org)  
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technology has contributed immensely to the sustenance of population of the country at present level.

Issues such as climate change, land-use changes, growing urban demand and environmental requirements continue to influence adversely sustainable water resources development and management. Research and development (R&D), often referred as the engine of prosperity, provides the underpinning for use of best available technology in water sector, and optimum use of available resources. It can safely be said that the one and only way to circumvent water-related issues is manifold increase in technical innovation to facilitate optimum utilization of scarce resources; which in practice trickles down to increased R&D efforts in the water sector. In the above context, this study takes an overview of existing water management practices in Bangladesh; and identifies the major challenges facing water management today. Further, the role of hydrological services is focused on, including the need for targeted R&D.

## **II. Water management and key issues for Bangladesh**

### **VI. Background**

Temporal and spatial distribution of rainfall in our country is highly skewed; with about 75 % rains falling during three monsoon months in most parts of the country. Water resources are under increasing competition because of burgeoning population with increasing affluence demanding more water in the form of agriculture, industry, domestic and hydropower needs. Water management for the society today is very complex, and involves diverse activities that are administered by different players. Major components constituting present day water management are classified below:

- 1) Water allocation: Apportioning of water to major users and uses; maintaining minimum levels for social and environmental use, while addressing equity and development needs of society.
- 2) River basin planning: Preparing and updating the basin plan as per need by incorporating stakeholder views on development and management priorities for the basin.
- 3) Stakeholder participation: Implementing stakeholder participation as a basis for decision making that takes into account the best interests of society and the environment in the development and use of water resources in the basin.
- 4) Pollution control: Managing pollution using socially acceptable principles and appropriate incentives to mitigate environmental and social impacts.
- 5) Monitoring: Implementing effective monitoring systems, which provide needed management information to identify and respond to infringement of laws/ regulations/ permits.
- 6) Economic and financial management: Applying economic and financial tools for investment and cost recovery to support the goals of equitable access and sustainable benefits to society.
- 7) Information management: Providing essential data necessary to make informed and transparent decisions towards sustainable management of water resources.

### **VII. Existing practices**

The above-mentioned activities, generic to water management in the country, are beset with a number of challenges that put these services at risk. Bangladesh is undergoing rapid economic

development and urbanization; with the current water development and management systems proving to be not sustainable. Lack of adequate storage is a major challenge in water resources development. Consequently, groundwater resources are being increasingly used, even to the extent of over-exploitation. Groundwater constitutes over half of Bangladesh's total water use; with 60 % irrigated areas and 70 % domestic water supply depending on groundwater. More than 15 % of Bangladesh's food is estimated to be cultivated using non-renewable, mined groundwater. Water data are collected by different agencies in Bangladesh, and stored at varied locations, with no common umbrella available. This leads to difficulties in accessing all relevant data by employees in different departments. Some states make limited amounts of information available to the public; resulting in politicians, domestic, industrial and agricultural users not making optimal decisions due to a lack of information. This can exacerbate water resources issues. Another challenge is the disconnection between management of surface water and ground water. Experts/administrators in each field are usually located in different departments, with different management structures. Further, the data management tools used is often different for surface and ground water. For example, in Bangladesh the application software MIKE and HYMOS are used for surface water analyses; and GeoWin and GEMS for ground water. This makes it difficult for the state agencies to derive the most value from their water, with surface and ground water resources not considered together.

Apart from additional storage, there is an urgent need for improved management of water resources at all levels.<sup>3</sup> Irrigation management is a case in point, where potentially large reduction in quantum of water use is feasible. A framework of agricultural, engineering and socio-economic measures is needed for effecting and efficient use of irrigation water supply. Agricultural measures include: deep cultivation, developing crops resistant water stress, improving soil moisture availability and staggering of water requirement for the crops. From socio-economic point of view, we need to see water as an economic good for which a rational price may need to be attached to protected water supply, similar on the lines of power supply. Further, users of irrigation water need to be protected by maintenance of an effective system of legally enforceable water-rights and other water-legislation. Engineering measures are simultaneously needed to be enforced for sustainability in irrigation water supplies. Such measures include: periodical risk analysis, integration of small reservoirs with major reservoirs to ensure that benefits are maximized, improving efficiency of water conveyance system by better operation and maintenance procedures including rehabilitation and modernization measures wherever warranted. This warrants planned implementation of lift irrigation schemes in association with canal-water supplies; and conjunctive use of surface and ground water helps in combating water-logging and Stalinization of farm-land.

### **VIII. Need for hydrologic design aids and generic DSS models**

Skills and knowledge are built up in individuals through years of experience and 'on-the-job' training. Modelling expertise within states tends to be limited to a few individuals. This expertise allows water resources managers to operate their systems using engineering judgments, often based on a highly developed 'feel' for the situation. When managers want to run test scenarios for short-term planning or to test the feasibility of infrastructure projects, they are fully reliant on the skills of a few modelers available at that time. When key personnel are lost due to factors such as transfer and retirement, the expertise is often lost irretrievably. Individual managers and technicians who are entrusted with water management functions at central/ state/ other agency

levels do generally a good job in operating often complex systems to deliver best services to a wide range of users. Good managers and technicians are no substitute for improving and systematizing water management practices through good, generic decision support system (DSS) models that can address issues such as providing access to common data; enhancing institutional capacity for decision making; publishing key data to inform the general public; and assisting short and long term planning through modeling<sup>4</sup>. DSS systems gainfully employed in water management include: simulation models for surface water planning, reservoir optimization with forecasted stream flows, drought monitoring/ assessment, flood forecasting and management and integrated water resources management. Section III.I.III details certain focused national efforts in this direction. One issue that irks water management in Bangladesh is the low use of data in design of projects. Very often, designs of projects are done by empirical/ rational methods. The principal reasons for this approach are: difficulties in accessing all relevant records, processing and analysis, absence of specialists such as hydrologists and hydro geologists in design offices and lack of established design aids.

### **IX. Water management issues**

Coupled with problems co-existing with present-day water management practices afore-described, modern-day water resources management is beset with the following key issues arising from the vagaries of hydrologic cycle and other extraneous factors.<sup>5</sup>

#### *Increasing vulnerability to severe events*

Inter-Governmental Panel on Climate Change (IPCC) highlights the potential for more frequent and more severe weather conditions; which is corroborated by many instances of extreme hydrological events. Such eventualities, coupled with increased pressure on land from the increasing population, will make safety of life and property high on the agenda for administrators and planners.

#### *Urban demand*

More than 60 percent of Bangladesh population is projected to live in urban and semi-urban areas by 2015. People, and the ever-growing industrial sector, will demand an increasingly larger share of the total water available; much of which is liable to be diverted from water meant for irrigation; which in turn can place greater pressure on water supply systems, and reduce availability of arable land. Accelerated urbanization has also the potential to create substantial pollution load on freshwater supplies and estuaries, which needs to be addressed. With urbanization comes the problem of the less privileged in the society often flocking to flood plains of rivers, thus creating additional technological and socio-economic issues concerning flood management.

#### *Unrestricted extractions*

Often, there is neither a management plan nor restrictions on water extraction from scarce resources. Water being the ultimate ‘commons’, and since water resources are no longer boundless, communities need to study water systems and re-define wise use.<sup>7</sup> Changes in human values, and ideas of morality, are needs of the day as regards water usage to avoid a situation where rational pursuit of individual self-interest can lead to collective ruin. Ground water extraction in large parts of Bangladesh is a classic example in this respect.

### *Climate change*

In general, analyses and application of management techniques in water sector have all along been carried out based on the presumption that hydrological series are stationary. There is growing evidence of shifting trends in such series, which need to be assessed and ascertained to enable taking corrective actions as needed. Periodic review of hydro meteorological networks for arriving at optimum network also assumes significance in this respect, as brought out under Section III.I. There is growing evidence of warming climate, as spelt out by climatologists, which can spell misery to the population in such regions. IPCC warns that climate change is expected to exacerbate water scarcity situation in Asia, with consequential multiple socio-economic stresses.

### *Allocation problem of existing supplies*

A typical water-supply system to a city involves structures such as reservoirs, canals, pumping systems, pipes, etc.; which are generally designed and allocated on the basis of past availability and existing demands. The current and/ or future availability does not often form a part of the scheme of things. This makes many water supply systems over-allocated. Studies show that, in general, lower the data length, higher is the likelihood of over-estimating water resources availability in a region. Uncertainties in respect of flood potential assessment too increase. Such factors warrant review of allocation of water supply systems and safety aspects from flood hazards periodically.<sup>8</sup>

### *Land-use changes*

Land use change is a reality, with more forest/ arid/ marshy/ fallow areas paving way for activities such as mining, agriculture, tourism-related activities and infrastructure development. For instance, a large number of mega power projects coming up on the eastern coastal region of Bangladesh. Expanding plantations and decreasing forest cover also play a major part in this scenario. Changes to land use, even within agricultural lands, have substantial implications for both water availability and use.

### *Environmental requirements*

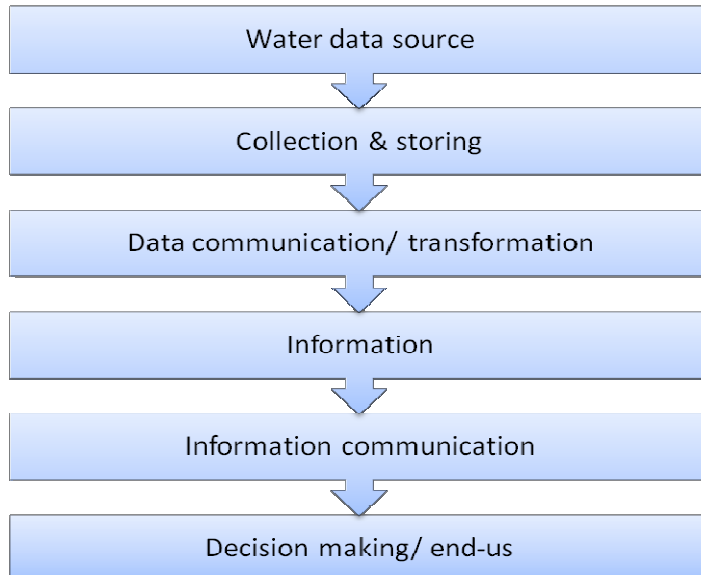
Environmental concerns are foremost on the minds of administrators, planners and the general populace; with the result that there is a steadily increasing awareness and emphasis on the requirements of environmental flows in any river system towards maintaining ecosystems such as wetland and in-stream environs. We have begun accepting the rights of nature, treating rivers, estuaries, forests and the like not as simply properties, but entities who have their own right to flourish. The day is not far of wherein this right would be put into statute, which would enable a vigilant citizen to file a suit on behalf of, say the injured watershed, arguing that its health is crucial to the common good.<sup>9</sup> In the above context, the ensuing sections detail the wherewithal to counter the issues by sustained scientific and technological initiatives in the hydrological services regime.

## **III. Hydrological services**

### **A. Monitoring, analysis and assessment**



The value of information for sustainable water resources development is self-evident. Information is a product of basic data, operated upon by mathematical, statistical, hydraulic, hydrological and other optimization models. Specific information to be produced would depend on recognition of the problem, and its subsequent solution using the relevant model(s). If the database is well designed and the models well documented, the same data can produce different varieties of information, with each one capable of being used in different situations. Hydrological information system (HIS) forms the backbone of water resources activities for a country; providing reliable data for long-term planning, design and management of resources and water use systems, and for research activities in related areas. In Bangladesh, primary data for HIS are collected, processed, stored and status reports brought out by agencies such as BWDB, Bangladesh Meteorological Department (BMD), State Irrigation/ Agriculture/ Public Works/ Water Resources Departments, etc. HIS, in practice, comprises data collection and storing system, data communication/ transmission system, data transformation system for producing information and information communication system, which in turn leads to inputs to informed decision making by the end-users, as delineated below.



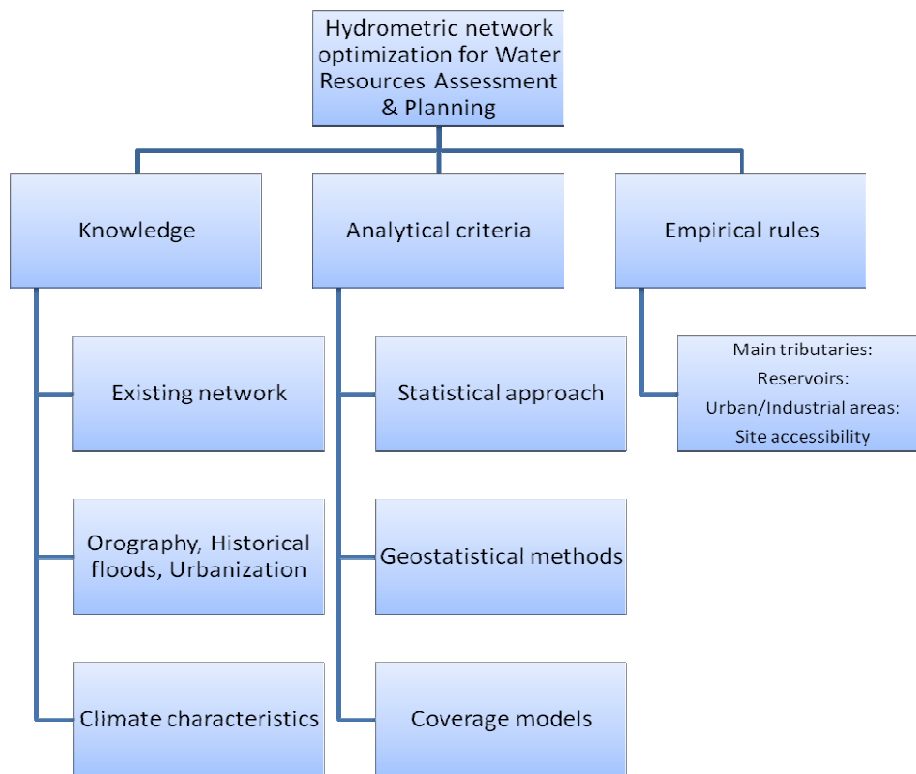
**Figure 1. Hydrological information system (HIS).**

Data transformation is in practice done by models, which can range from simple statistical models, hydrologic design aids, monograms, involved DSS models and the like. HIS is central to sustainable water development, with its output having a wide variety of users, both in the public services domain and in private sector. Users fall under the broad clusters of large scale and repeat users, and occasional or one-time users. A majority of the users in the public services domain belong to the former; whereas, most users in the private sector are likely to belong to the latter category. For instance BWDB, IWM, CEGIS are sophisticated users of water data; with the organization using data extensively in physical, mathematical, hydraulic, hydrologic and other models while conducting applied/ specific research studies pertaining to water resources. Large scale and repeat users of HIS mainly belong to various policy level and operational level government departments, financial institutions, command area development agencies, irrigation/ water resources departments, public works departments, NGOs, etc. Occasional users are of two

types: those who need to find and use water in a micro-geographical area for their own use, and those who need to find and use water for commercial purposes or community activities.

### 1. *Hydrologic network*

The hydrological network includes subsystems for measuring stream flow, precipitation, groundwater, evaporation, etc.; and provides water-related data for HIS. Thus, for a river basin, the hydrometric network for measurement of stream flows forms a subsystem of the hydro meteorological network. Setting up and maintaining such a network is an evolutionary process, wherein a network is established early in the development of the geographical area. The network needs to be reviewed and upgraded periodically to arrive at the optimum network. Different approaches exist for optimization of a real life network, as delineated in Figure 2.



**Figure 2.** Approaches to network..

### *Modelling capabilities*

A major challenge for future in water resources sector will be development of analytical and modeling techniques, which would enable holistic approach to resource management. Advances in modeling capacities are closely associated with advances in computers, and the interaction between modelers of hydrologic systems, programmers and hardware specialists. Hydrologists make use of GIS technology to integrate various data and applications into one manageable system. With a large number of water resources projects in different stages of planning and execution, the need for modeling skills is all the more pronounced, especially for hazard assessment. To usher in uniformity of approach among state and central agencies in water data dissemination, work is under way for development of standardized hydrological design aids (HDA) using well-established, internationally acceptable methodologies. HDA aims to provide a

platform for simplifying and making more accurate a range of hydrological analysis tools and associated guidance for users across Bangladesh; and would facilitate and expedite hydrologic design and assessment of surface and ground water resources.

#### **X. Products and services**

Collection of hydro-meteorological data using instruments, and transmitting them to wherever the data are needed for analysis and decision making, form an important component of HIS. Use of new products and services that are designed to enhance the quality and speed matters in water resources management applications. Short message service, internet, cloud computing and other future developments in these areas will be of vital interest. Acoustic Doppler Current Profilers (ADCPs) are established tools for water management in riverine and coastal environment, which are increasingly being used in Bangladesh. Likewise, Integrated Bathymetric System for Reservoir Sedimentation Survey (IBSRSS) makes it easier to carry out hydrographic survey of reservoirs.

Under IWM, BWDB upgraded the Current Meter Rating Trolley (CMRT), and refurbished the rating tank facility to meet current meter calibration requirements in accordance with the relevant national/ international standards. The upgraded CMRT is equipped with instruments based on state-of-the-art technology such as variable-speed servo motor drives with programmable logic controller for precise trolley speed control in the range of 0.01 m/s to 6.0 m/s; and real-time data acquisition and processing system capabilities for current meter calibration.

#### **XI. Research**

For each case involving water resources development and management, the optimal solution needs to be obtained and fine-tuned, to match site-specific conditions and user's expectations through R&D. With the increasing demand on water resources, and an increased awareness of resultant environmental impact of conducting and operating physical works that alter natural flow regimes, more and more questions would routinely be raised during project formulation stages regarding the before and after comparison of proposed projects. For sustainable water resources development, topics like these, and numerous others, naturally become subjects of R&D. Moreover, the intensity of external effects in water use is greater than in any other sector of the economy; which is why water resources have very often been a publicly managed or regulated resource. For the reasons above-mentioned, in Bangladesh, the magnitude of investment from the national exchequer in water resources is huge, calling for the use of best available technology to manage the investment; which translates to need for effective R&D in the water sector. Water resources R&D falls into three broad categories: basic, specific/ applied and action research. Basic research comprises investigations or studies of specific problems, which add to the theoretical knowledge that may or may not find immediate applications, but would definitely advance technology for future applications. Basic research also provides necessary inputs for applied research on specific problems. Specific/ applied research studies are those for finding appropriate solutions to the problems confronted by engineers in the field, based on the available research knowledge. Often, specific research is referred as applications. Applications can essentially be either 'works' or 'studies' carried out for specific purposes. Works may concern hydraulic and hydro-informatics investigations and design developments carried out and implemented. These also may be related to actions such as design and

implementation of decision support systems, riverine water quality monitoring, real time flood forecasting systems etc. Action research includes studies on pilot projects, field problems, and those investigations relating to model prototype conformity to put available research results, to test, in order to assess their validity for practical applications. Holistically looking, sustainable water resources development is an integrated activity involving engineering and economic issues as well as resource policies. Water resources projects are sustainable, if water of sufficient quantity and quality is available, at acceptable prices, to meet the demands and quality standards of the population of the region now and in the future without causing the environment to deteriorate. Sustainability must be the concern of project planner and all engineers and scientists involved in the planning process of a water resources project. However, technical skills alone are not sufficient to make a system sustainable. Sustainability also requires a willingness to go beyond the scope of standard technical solutions, for which better understanding of the interaction of the system with its surroundings and with other uses is necessary.

#### **IV. Conclusion**

Modern technology has contributed immensely to the sustenance of Bangladesh population at the present level. Water, through its development, conservation, control and protection enters into infrastructure in a big way. The key to sustainable water resources development in the country is effective use of innovative techniques in the sector, which in practice, translates to larger role for R&D to find ways and means for tackling inefficiency and waste, both in delivering water-services and in responding effectively to water demand. Issues such as climate change, growing urban demand, land-use changes and environmental requirements continue to influence adversely sustainable water resources development and management. R&D provides the underpinning for use of best available technology and optimum use of water resources. In the above context, this study has given an overview of the existing water management practices in the country, and identified the major challenges facing water resources management today. Such challenges include climate change, increased vulnerability due to extreme events, rising urban demand of water and consequential change in water dynamics, allocation problems relating to existing demands, unrestricted extraction of water resources and environmental requirements. Also elucidated is the role of hydrological services including focused R&D in resolving the varied issues. R&D efforts in water sector are shown to assume two major roles in furthering sustainable water resources management: i) in helping to decrease the vulnerability by furthering development and increasing adaptive capacity, and ii) by giving an option to respond to numerous contingencies that an unknown future holds. In an information-based global economic system, all knowledge has potential economic value. However, in the modern-day information and communication technology led R&D era, universities, research centers and researchers are no longer in total control of the definition and production of knowledge; but are simply actors in a multi-sectorial social, political, scientific and technological enterprise. This augurs well for setting the ground for technical innovation in varied areas, especially water sector; where high technology is a historical necessity on account of the ever-burgeoning human population and consequential water demand.

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# Coastal Reservoir-The Trend Of Water Supply In New Era

Shu-Qing Yang<sup>a\*</sup>

**Abstract:** Water shortage can be caused by population growth that drives the growth of water demand for domestic, agricultural and industrial purposes. Water shortage in water-rich areas can be also caused by water pollution. The water problem caused by poor quality and insufficient quantity has been widely noted and well informed among the researchers, decision makers and ordinary people, but not much research considers these facts: 1) more and more people migrate to coastal areas; 2) sedimentation by soil erosion reduces the storage capacity of existing reservoirs and many of them will be out of use in the next 50 years; 3) for developed countries like Australia, it is almost impossible to build new inland dams to replace the lost storage. Thus, a major issue is to find new sources of drinking water for the future. This paper describes the potential benefit of expanding the use of coastal reservoirs for human consumption. First, we review current issues associated with water supply; then, we identify key differences between inland and coastal reservoirs before highlighting advantages of coastal reservoirs in the future.

**Key words:** Coastal reservoirs; Inland reservoirs; Seawater intrusion; Freshwater development; Runoff harvest.

## I. Current Water Supply Infrastructure Under Pressure

Water is the foundation of life. Unfortunately, approximately 1.1 billion people can't access safe drinking water; 2.6 billion people lack adequate sanitation, and 2 to 5 million people die every year from water-related diseases<sup>1</sup>. To meet irrigation demand for agriculture by 2025, the World will need an additional 192 cubic miles of water per year; a volume equivalent to ten times the annual flow of the Nile river<sup>2</sup>. Thus it is urgent to identify new sources of water that will meet future human, agricultural and industrial needs.

## XII. Increasing Demographic Pressure on Coastal Areas

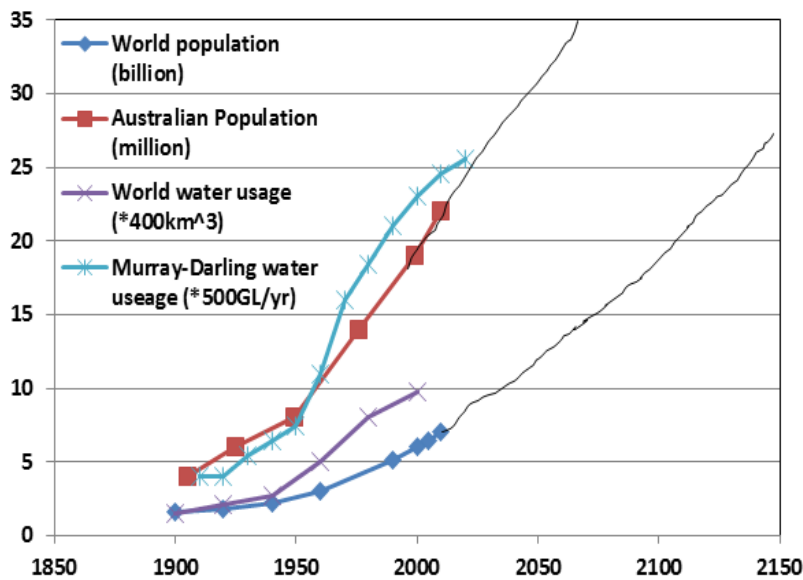
As shown on Figure 1, World and Australian populations steadily increase. At current rate, total population could double within the next 50 years. A significant proportion of this growth will be concentrated along coastal areas thanks to regional migrations.

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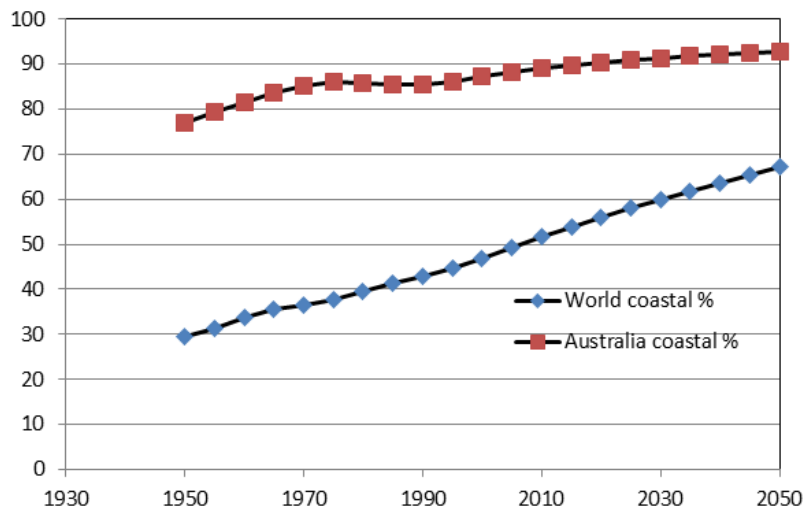
<sup>a</sup> School of Civil, Mining and Environmental Engineering, University of Wollongong

\*Corresponding author: Shu-Qing Yang, [shuqing@uow.edu.au](mailto:shuqing@uow.edu.au)  
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Figure 2 shows the percentage of people living in coastal areas. In Australia, 70% of people lived along coastal areas in the 1950s; this percentage has now reached 90%. Similarly, 30% of the World population lived along coastal areas in the 1950s and this proportion has now reached 70%. Historically, major reasons for this attraction include the fact that coastal and deltaic areas are very productive ones in terms of agricultural and fisheries resources. They also offer natural waterways for transport and relatively flat topographies for industrial and residential development. More recently, increased mobility and attention to lifestyle associated with ageing populations retiring down the coast *en masse* have increased migration flows. Unfortunately, current water reservoirs are located and sized according to past demographic patterns and it is fair to ask whether coastal areas, especially in Australia, are ready to accommodate so many people in a near future?



**Figure 1.** Australian and World population growth and water usage, 1850-2150 period.



**Figure 2.** Percentage of coastal population in Australia and in the World, 1950-2050 period.

### **XIII. Lifespan of Existing Reservoirs**

The lifespan of a concrete dam is usually between 100 and 200 years. But the lifespan of a reservoir also depends on its sedimentation rate<sup>3</sup>. The total sediment yield in the world is estimated to be  $13.5 \times 10^9$  tons/year or 150 tons/km<sup>2</sup> per year. About 25% of this is transported into the oceans and 75% is trapped, retained and stored in the lakes, reservoirs and river systems (Batuca and Jordaan, 2000). As a consequence, silting is reducing the storage capacity of water reservoirs world-wide by more than 1% per year.

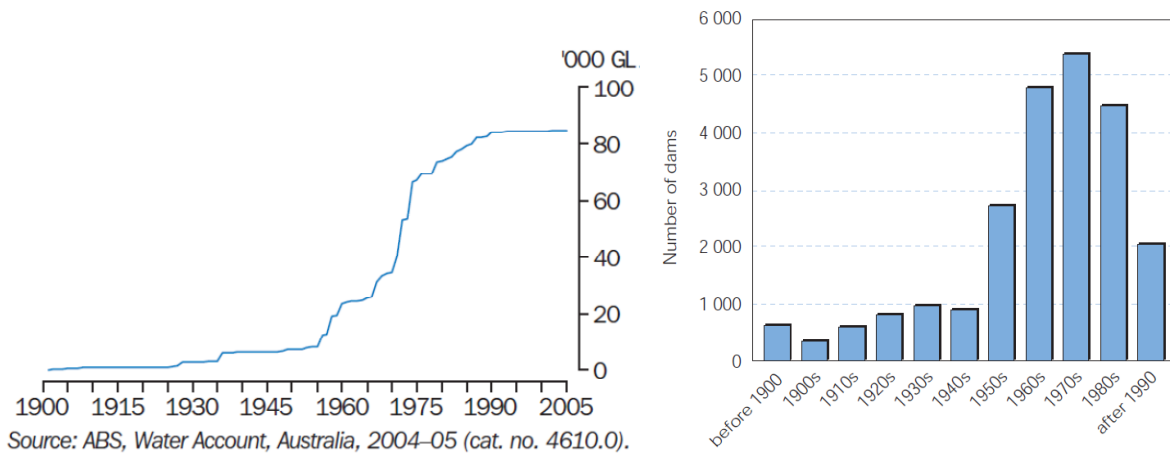
James and Chanson<sup>4</sup> argue that “Australian reservoirs [are] subjected to very high siltation rates that are comparable to overseas most extreme ones”. Australian reservoirs, compared to the rest of the world, are subjected to extreme arid and semi-arid climatic conditions whereby dam volumes can range from near-empty to full, often with rapid filling periods<sup>5</sup>. Under such abrupt conditions, river flows carrying upstream sediments into a reservoir are unsteady and non-uniform. Unfortunately, we still have a limited understanding of sediment transport in non-uniform stream flows while its consequences matter for many engineers and other professionals.

Sediment is also the largest single pollutant to ecosystems as stressed by the Environmental Protection Agency in their Report to the US Congress (National Water Quality Inventory Section 305b). In Australia, every year, algal blooms cost between A\$180 and A\$240 million<sup>6</sup>. Eutrophication, a major factor of coastal algal blooms, often result from a high sediment load that has elevated levels of colloidal material, phosphorus and Nitrogen. Davies-Colley et al<sup>7</sup> showed that an increase in suspended sediment of ~30 mg/l in a previously clear stream can result in a 50% reduction in plant production. Hence the prediction of sediment transport is crucial in addressing many environmental problems, including impacts on river morphology and ecosystems.

### **XIV. Can We Build New Inland Dams?**

As per Figure 2 above, most people will live in coastal areas by 2050. Meanwhile, many existing inland reservoirs will be out of service due to the gradual decrease of their storage capacity through siltation. Unfortunately, the number of suitable sites for inland reservoirs near the coast is very limited. Figure 3 (right) shows that the number of new dams being built world-wide has sharply decreased since the 70s. All suitable locations will probably be exploited by 2050. In Australia (Figure 3, left), construction of new inland dams has come to an halt. For example, proposals for the Tillegra dam on the Williams River (NSW) and the Traveston Crossing dam on the Mary River (QLD), were both cancelled due to fierce campaigns from local communities. As a matter of fact, public opinion is increasingly concerned with inland reservoir's potential devastating effects on rivers, freshwater ecosystems, and the people who depend on them. Currently, the Australian and State Governments embrace a ‘no more dam’ strategy preferring to turn towards more expensive and sophisticated technologies like the construction of desalination plants or wastewater recycling plants. Are people ready to pay the real cost associated with these new sources of water? Coastal reservoirs might provide an alternate sustainable and affordable solution.





**Figure 3. Cumulated storage capacity in Australia (left) and number of dams built in the World (right), 1900-2000 period.**

## II. Coastal Reservoirs, Definition And Applications

Coastal reservoirs have the potential to become a major source of freshwater in coastal areas, alongside existing inland reservoirs, desalination plants, wastewater recycling plants and rainwater tanks. By definition, a coastal reservoir is a freshwater storage located in coastal waters (river mouth, lagoon or protected bay) being fed by a sustainable freshwater flow. Coastal reservoirs have an impermeable barrier protects the freshwater storage from intrusion by the surrounding brakish seawater. Depending on its location, water captured in a coastal reservoir will be of varying quality for domestic, agricultural or industrial water use. In some cases, integration with other water schemes is possible (desalination or wasterwater recycling). Currently the world only uses about 1/6 of its surface runoff, the remaining being lost to the oceans. Despite its overall arid climate, Australia sees approximately 279,000GL of freshwater being flushed to the oceans every year, while only 21,000GL is being harvested and used. Henceforth, Australia only uses 7.5% of its annual runoff , which is one of the lowest harvesting rate in the world.

Coastal Reservoirs have significant advantages due to their positioning near a river mouth. As reservoir and sea levels are nearly the same and thanks to the lower density of freshwater compared with seawater, risks of seepage are minimal. Likewise, as water pressure tends to reach an equilibrium on both side of the impermeable barrier, this barrier does not need to be highly resistant to pressure as it is the case with inland dams. Coastal Reservoirs are already being used in China, South Korea, Hong Kong and Singapore (see Table 1) and have been largely successful, especially in places where there are no more opportunities to build inland reservoirs. Plover Cove dam in Hong Kong is the first coastal reservoir in the world specially designed for providing drinking water. The Qingchaosha reservoir, located at the mouth of the Yangtze river, has the longest dam.

**Table 1. Existing coastal reservoirs in the World**

Name	Catchment (km <sup>2</sup> )	Dam length (m)	Capacity (10 <sup>6</sup> m <sup>3</sup> )	Year completed	Country/river
Qing Chaosha/Shanghai	1.8million	43,000	553	On-going	China/Yangtze
Saemanguem	332	33000	530	2011	South Korea
Sihwa		12400	323	1994	South Korea
Marina Barrage	113	350		2008	Singapore
Chen Hang/Shanghai	1.8million	4700	8.3	1992	China/Yangtze
Yu Huan	166	1080	64.1	1998	China/ Zhejiang
Baogang/Shanghai	1.8million		12	1985	China/Yangtze
Plover Cove	45.9	2000	230	1968	Hong Kong



**Figure 4. Plover Cove Dam, the first coastal reservoir for drinking purpose in the World.**

Comparing characteristics of inland and coastal reservoirs (Table 2), we may conclude that the two of them are totally different. For example, inland reservoirs can only collect water from part of a catchment, and their size is generally whereas coastal reservoir have the potential to harvest any single drop of rain from the catchment as its size is theoretically unlimited. The construction cost of an inland reservoir is generally very high due to the need to build high and strong dam walls, while the pressure force on both sides of the barrier of a coastal reservoir is generally small, although wave surge and tides might be of concern for its design. The most challenging problem for designing a coastal reservoir is to prevent excessive pollution as pollutants carried by the river from the whole catchment are likely to be collected by and trapped in the reservoir. Sihwa Lake, located in South Korea, provides a dramatic demonstration of such a failure. This coastal reservoir was initially designed as a freshwater supply source. In 1994, a 12.4 km-long wall was built to separate Sihwa Lake from the sea; but severe water contamination occurred, resulting from an excessive inflow of polluted wastewaters, mainly from a nearby industrial complex. In order to improve the water quality of the lake, the decision was to abandon the original freshwater reservoir scheme and allow seawater exchange. In 2005,

seawater entered into the lake and the reservoir has been converted into a tidal power generation plant.

**Table 2. Difference between inland and coastal reservoirs.**

	<b>Inland Reservoir</b>	<b>Coastal Reservoir</b>
Dam-site	Limited by topography	Unlimited (inside/outside river mouth)
Dam design	High pressure	Low pressure but with wave/tidal surge
Seepage	By pressure difference	By density difference
Pollutant	Land lased	Land-based + seawater
emigrant cost	High	No
Water supply	By gravity	By pump
Water catchment	Small part	Whole catchment

**Table 3. Comparison of different proposals to provide 500GL/year**

	Inland dams	Desalination	Recycled wastewater	Coastal reservoir
Energy used (in $10^9$ kWh)	0	2.0	1.0	0
CO2 emission (in $10^6$ ton )	0	3.33	1.67	0
Construction cost (in billion A\$)	11.42	9.28	10	2.8
Maintenance and operation cost	Low	High	High	Low
Ecological Impact	Loss of biodiversity	Low	Low	No impact
Life span	100 years	20 years	20 years	Infinity
Sustainability	permanent damage	remediable damage	sustainable	sustainable

### III. A New Era For Water Supply Infrastructure Provision

Existing solutions to alleviate current and future water deficit world-wide include inland dams, wastewater recycling plants, desalination plants and coastal reservoirs. Table 3 compares these different technologies assuming, by way of simplification, that unit costs (energy or gas emission) per GL of water remains constant when it is expanded to 500GL. For example, if one method costs  $x$  (in A\$/GL), then  $500x$  (in A\$) is needed for this method in Table 3. The comparison clearly indicates that coastal reservoirs are technically feasible, environment-friendly, sustainable and cost effective. Table 4 provides suggestions for future coastal resrvoirs around the World.

**Table 4. Potential sites for future coastal reservoirs around the World.**

Location	Rivers & annual runoff ( $10^9 \text{ m}^3$ )	Specific Conditions
West coast of USA	Hood, Klamath, Eel, Sacramento (21)	River mouths + coastal canal
Egypt	Nile (11)	Using existing lagoons (Mariut, Edku, Burullus...)
Iran, Iraq and Kuwait	Kishop, Tigris and Euphrates (55)	Cross-boundaries management
China: Beijing, Tianjin, Shanghai & Guangzhou	Yellow, Yangtze and Pearl (2000)	Reservoirs on river outlets
Kuala Lumpur and Singapore	Langat, Selangor, Bersama and Johor (150)	Reservoirs on river outlets
Australia: Brisbane, Newcastle & Adelaide	Richmond River, Hunter River, Shoalhaven River, Murray Darling River (?)	Reservoirs on river outlets

#### IV. Conclusion

After analysing future population growth and water demand we have reviewed existing technological solutions and the following conclusions can be drawn from this study:

- 1) In the next 100 years, the population and water demands may continue to increase significantly;
- 2) Most of people in future will live in coastal and deltaic areas.
- 3) The distribution of existing inland reservoirs will not match the future population distribution;
- 4) Many existing inland reservoirs will be out of service by 2050 due to siltation;
- 5) Coastal reservoirs offer a sustainable, cost-effective and clean solution for futurer water supply.

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# A National Scale Infrastructure Database and Modelling Environment for the UK

Stuart Barr<sup>a\*</sup>  
David Alderson<sup>a</sup>  
Craig Robson<sup>a</sup>  
Alex Otto<sup>b</sup>  
Jim Hall<sup>b</sup>  
Scott Thacker<sup>b</sup>  
Raghav Pant<sup>b</sup>

**Abstract:** Reliable, consistent and detailed spatial-temporal data, information and knowledge on infrastructure assets is essential to inform the long term delivery of infrastructure systems. To leverage maxim utility integrated data management, analysis, modelling and visualization environments are required for this purpose. Within the UK Infrastructure Research Transitions Consortium (ITRC) a national scale spatial database, analysis and modelling system (NISMOD-DB) has been developed, that contains national scale data and information on infrastructure assets and networks, as well as, information and knowledge on the geo-temporal patterns of infrastructure demand, supply and capacity. In this paper we describe the main components of NISMOD-DB and how it can be used within infrastructure systems research.

**Key words:** Infrastructure Systems, Database, Spatial Networks.

## I. Introduction

While worldwide several large scale research initiatives have been instigated into developing a new suite of infrastructure analysis and modelling tools (e.g., US National Research Council report on Sustainable Critical Infrastructure Systems, Dutch programmes on Next Generation Infrastructure and Knowledge for Climate and the Australian Critical Infrastructure Protection Modelling and Analysis (CIPMA) programme), many challenges remain to be addressed before the full suite of analytical tools are available that will provide the key insights required to develop cohesive long term critical infrastructure plans<sup>1</sup>. Amongst these, a key consideration is the availability of good quality comprehensive data and information on critical infrastructure systems<sup>2</sup>.

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<sup>a</sup> School of Civil Engineering and Geosciences, Newcastle University, Newcastle Upon Tyne NE1 7RU, UK.

<sup>b</sup> Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX1 3QY, UK.

\*Corresponding author: Stuart Barr ([stuart.barr@ncl.ac.uk](mailto:stuart.barr@ncl.ac.uk))

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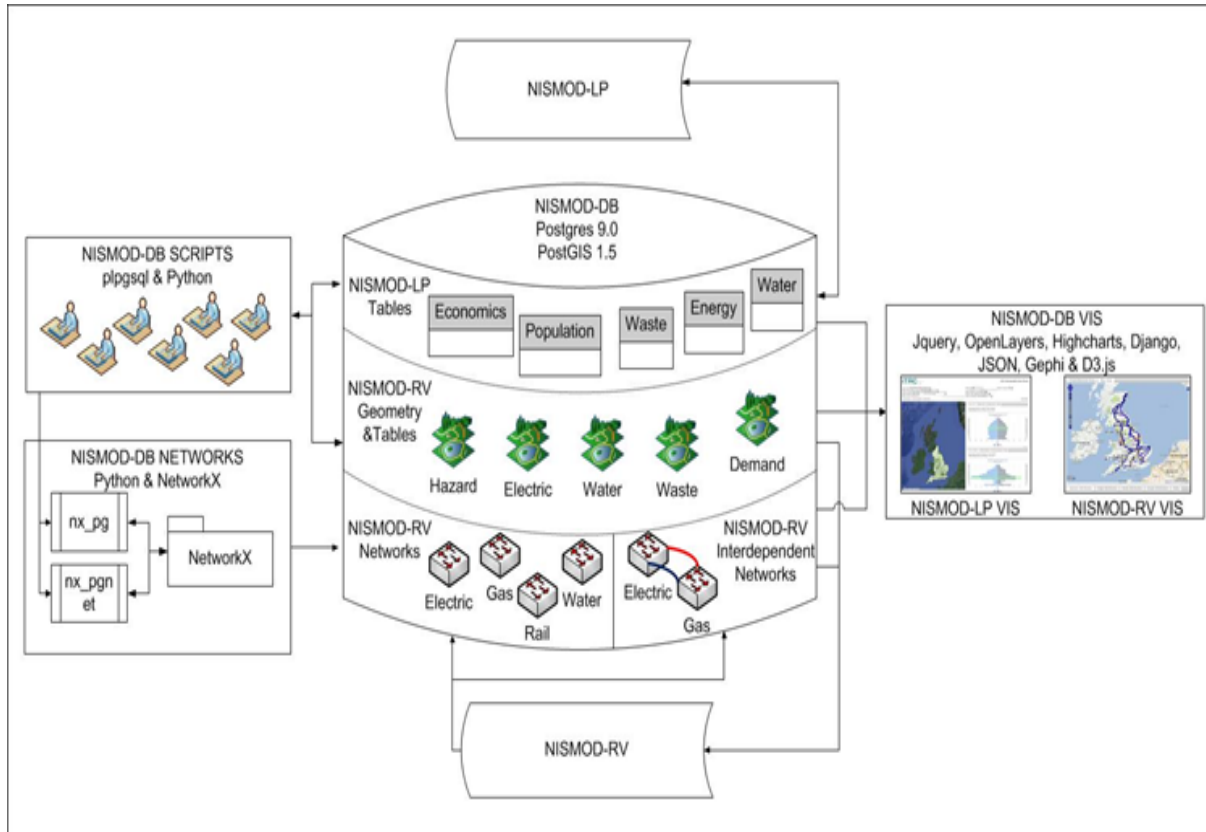
However, such data and information have limited applicability unless matched by suitable data management, analysis, modelling and visualization tools<sup>2</sup>, that allow the myriad of vulnerabilities, demand/capacity constraints and lifespan renewal issues of individual infrastructure systems to be considered in association with the dependencies and/or interdependencies that exist between them<sup>2</sup>. To address this challenge in the UK, the Infrastructure Transitions Research Consortium (ITRC) has developed a prototype integrated national-scale infrastructure database and analysis system (NISMOD-DB) to support modelling of the long term capacity/demand requirements of infrastructure (NISMOD-LP) and infrastructure network risk (NISMOD-RV). In this paper we present the prototype architecture and structure of NISMOD-DB and demonstrate how it allows an analysis of large scale data and information on infrastructure systems.

## II. THE ITRC NISMOD-DB DATABASE

### A. Overall Database Organisation

Figure 1 shows the overall design of NISMOD-DB. In addition to the database itself, it also has a series of related extension modules for analysis and visualization. The database also links to the modelling software of NISMOD-LP (the modelling of the long term capacity and demand of critical infrastructure systems) and NISMOD-RV (the modelling of interdependent infrastructure systems risk and vulnerability). One of the major aims of ITRC is to compile complete national-scale representations of infrastructure systems. Thus, NISMOD-DB must be able to represent the spatial (geographic/location) characteristics of infrastructure systems as well as their non-spatial properties. To achieve this *PostgreSQL* RDBMS, along with its spatial extension *PostGIS* have been employed. *PostGIS* allows spatial data layers in the form of geometry tables to be encoded and also provides a wide range of spatial operators and functions that can be used to process, analyse and manipulate the spatial infrastructure systems layers<sup>3</sup>.

In the database, tables are organized and grouped in terms of their use within ITRC and then in terms of infrastructure system (Figure 1). In the case of the long term capacity/demand modelling of NISMOD-LP, standard relational tables representing the required inputs and results of the modelling undertaken are stored and organised by economic, population (demographic), energy, water (clean and waste), transport and solid waste sectors. Data for the infrastructure risk and vulnerability modelling (NISMOD-RV) is primarily stored as *PostGIS* spatial geometry tables (point, polylines, polygons) representing the location and spatial extent of individual infrastructure system features. Again, these are organised and grouped by infrastructure system; namely, spatial hazards, energy (electric transmission/distribution, gas transmission/distribution), water (supply and waste), transport (road, rail, air, sea (ports)) and solid waste (Figure 1).



**Figure 1.** The overall organisation of the ITRC NISMOD-DB spatial database, analysis and visualisation framework and its linkages to other ITRC modelling software.

## B. Interdependent Infrastructure Network Models

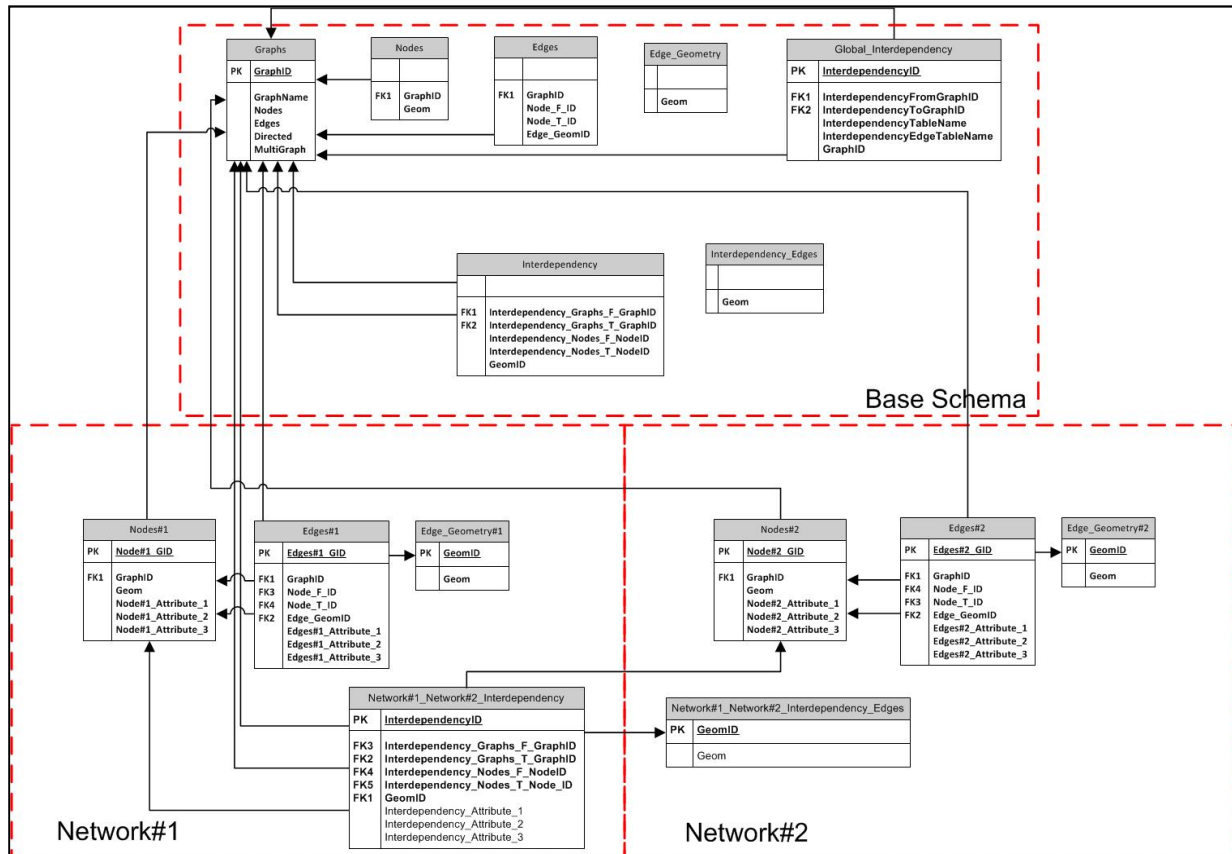
To facilitate the modelling of infrastructure networks within NISMOD-RV a bespoke interdependent network database schema has been developed in NISMOD-DB. This allows geometry tables representing infrastructure asset point and polyline features to be combined to build spatial-topological infrastructure network models (e.g., an electricity transmission network model from electricity substation points and transmission polylines), and the relationships between networks to be represented (Figure 2).

In the base schema the Graphs table keeps a record of all networks stored, while the Interdependency and Interdependency\_Edges tables allow dependencies or interdependencies that exist between two networks to be stored. Any network graph is represented by a Nodes table that contains both the attributes and geometry of the node data, while Edges and Edge\_Geometry tables contain the attributes and geometry of the edge data respectively. The modelling and storage of a specific network is accomplished by the specific network instance, or child tables, inheriting attributes from the parent tables of the base schema. By using inheritance, the instance tables are supplied with the minimum set of attributes, for both nodes and edges, required for a generated network model (single or interdependent) to be employed in subsequent analysis.



### C. NISMOD-DB Scripts

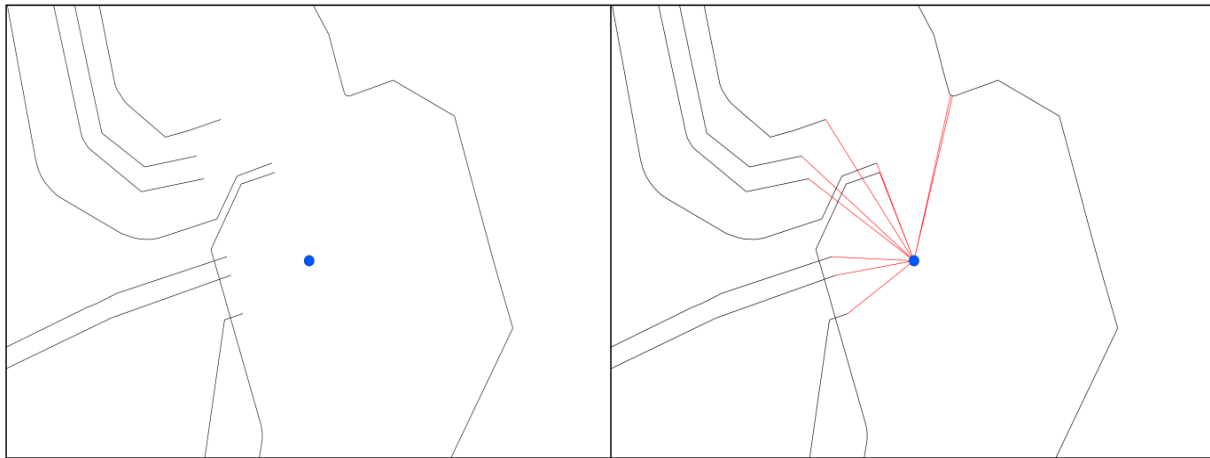
To manage and process the national data-sets held in NISMOD-DB a suite of processing scripts have been developed for database maintenance, network construction, pre-and-post network construction filtering and analysis (Figure1). Database management scripts have been written in the *SQL* procedural programming language *plpgsql* and are directly available in the database to perform administrative tasks such data import/export, creating, deleting, and setting primary and foreign key constraints between tables.



**Figure 2.** Entity relationship diagram showing the database schema developed for the representation of interdependent spatial infrastructure networks.

Individual or interdependent network models are created by a separate set of scripts, NISMOD-DB NETWORKS that have been developed in *Python* and act as a wrapper around the database (Figure 1). These scripts employ *NetworkX*, a *Python* package for the creation, manipulation, and analysis of the networks. *NetworkX* functions are used in two python wrapper modules; *nx\_pgnet* which converts two tables, one of nodes and one of edges stored within a *PostGIS* database, in to a network model that is subsequently stored using the custom network schema, and *nx\_pg* that allows node and edge tables in *PostGIS* to be read/written directly to/from *NetworkX* for analysis.

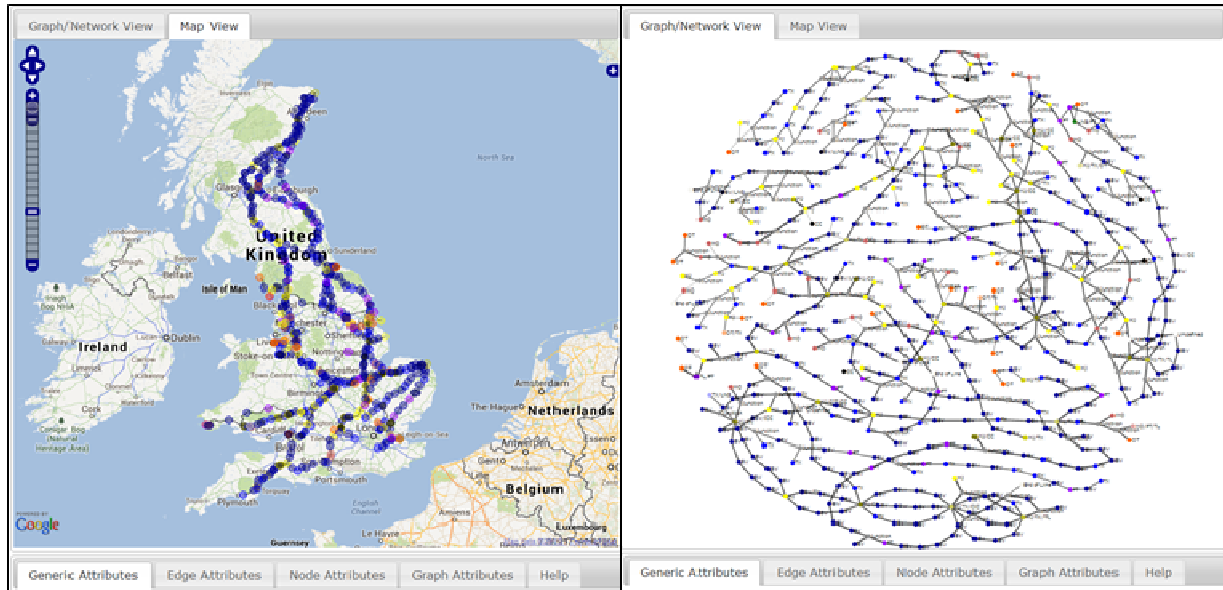
Modules for pre-and-post network construction clean and filter data to remove or correct systematic geometry or attribute errors that result in incorrect network models being generated. Examples of such functions are `EdgeToNode_SpSearch` and `EdgeToNode_AttLike`; the former connects the end point of an unconnected edge to its nearest node within a specified search distance. The latter performs a similar task but on the basis equivalence comparison between item values of specific attributes in a node and edge table respectively. Tools such as these can be used to connect hanging edges to nodes and can be used to remedy digitisation errors. Figure 3 shows the utility of such a suite of scripts, where the original UK National Grid Gas Transmission pipes do not intersect spatially with the gas compressor. Use of the script `EdgeToNode_AttLike` in this instance created completed edges between the pipelines and the compressor node on the basis of a comparison of the gas pipeline and gas node names.



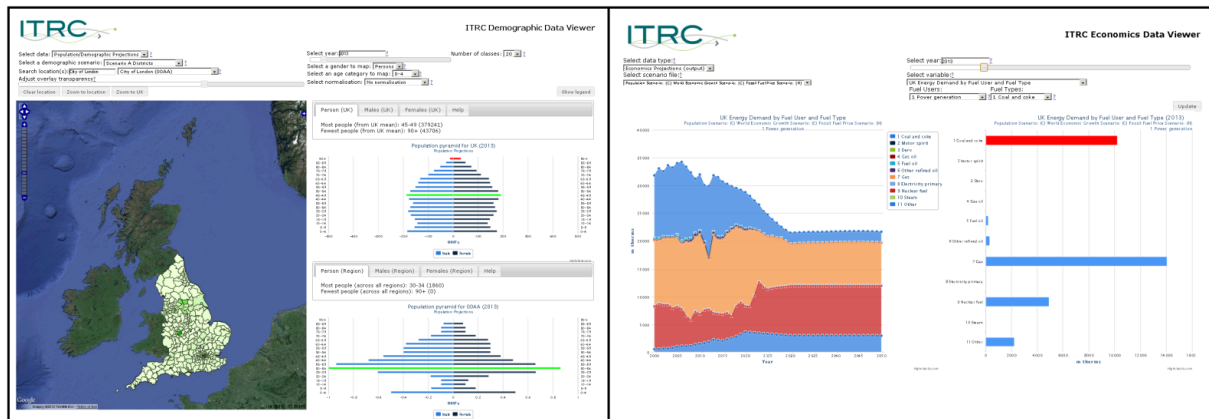
**Figure 3.** Use of network cleaning scripts to construct a topologically valid infrastructure network model for the national gas transmission network of the UK.

#### **D. NISMOD-DB Visualisation Engines**

Several prototype visualisation engines have been developed and coupled to the ITRC database; one each for NISMOD-LP and NISMOD-RV. The visualisation interfaces have been constructed using a *Django*-enabled web framework along with *OpenLayers* map client, *Google Maps Application Programming Interface* (API) and *Highcharts*. Data retrieval and querying of the database is performed via the use of synchronous AJAX requests that allow a user to directly retrieve data stored within the database and present this as a new map, plot, or time-series chart depending on the combination of the data, scenario, variable and dimension selected via the interface. Figure 4 shows two renderings of the UK National Grid Gas Transmission network; a geographic network model, and a graph rendering showing the topologically most important nodes derived by using the *NetworkX Python* wrappers described above. Figure 5 shows two views of the results of the NISMOD-LP modelling held in the database; in this case demographic and economic growth projections. In both cases spatial and a temporal component of the modelling are shown.



**Figure 4.** Two examples of the NISMOD-DB VIS outputs generated from the UK national gas transmission network model held in NISMOD-DB.

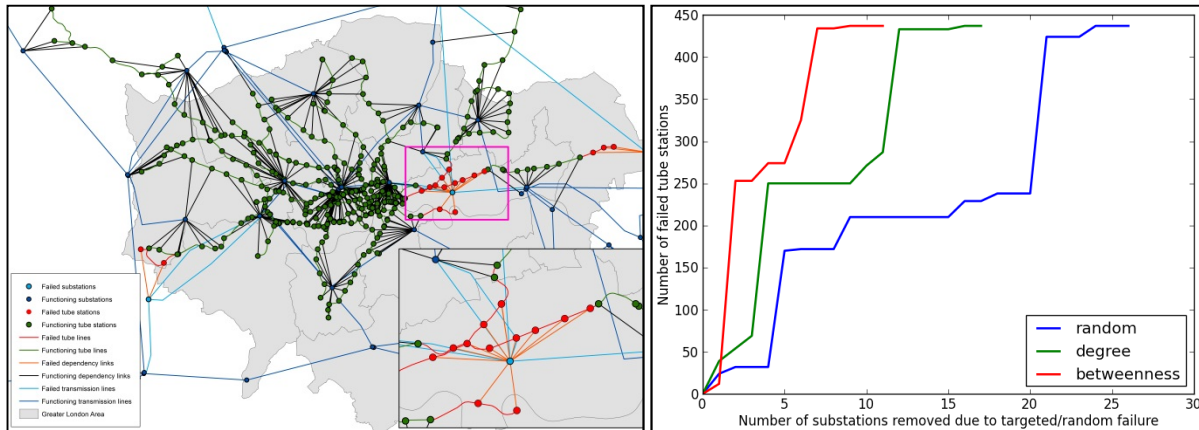


**Figure 5.** NISMOD-DB VIS generated views of the results derived from the capacity/demand modelling of NISMOD-LP using data stored in the NISMOD-DB database.

### III. INTEGRATED INFRASTRUCTURE ANALYSIS

The ITRC NISMOD-DB was employed in an analysis of the dependency of the London underground tube network on electricity transmission supply using a number of failure models. NISMOD-DB *PostGIS* geometry tables of the London underground (stations and rail lines) and the UK National Grid electricity transmission geometry tables for the south-east of England were converted into network infrastructure models using NISMOD-DB NETWORKS. The dependency between the London underground tube network and the electricity network was generated by assuming that each tube station is powered by its geographically closest electricity substation. A basic cascading dependency failure model<sup>4</sup> was coded for three types of electricity substation failure; random, ranked by betweenness centrality and ranked by degree<sup>5-7</sup>. In the model, a tube station fails along with its associated track if a substation it is dependent on fails.

Failure impact was assessed using a range of graph metrics<sup>8-9</sup>. Figure 6 shows the results for the three different types of failure. The map displays a single ‘state’ of the failure model. The plot shows that failures based on high degree and high betweenness have a more significant effect on the tube network than randomly introduced failures; implying that the London underground is more vulnerable to failure of the highly connected electricity sub-stations.



**Figure 6.** Interdependent infrastructure analysis using NISMOD-DB networks.

#### IV. CONCLUSION

In order to manage and plan infrastructure systems at a national scale suitable analytical tools are required. This has been recognised as being particularly important in relation to an improved understanding of interdependent infrastructure systems<sup>2</sup>. As recognised by Rinaldi et al<sup>2</sup> database systems and associated tools will play a critical role in the future management, analysis and modelling of individual and interdependent infrastructure systems. In this paper, we have described the developments that have been made in the UK ITRC project in the use of database technology for the management and analysis of national scale infrastructure systems. NISMOD-DB offers a flexible environment for the storage of a range of different infrastructure data, both spatial and aspatial. Furthermore, the development of a bespoke interdependent infrastructure network schema opens up the possibility of using the database as the foundation for complex infrastructure simulation modelling; results which can be readily visualised by coupling visualisation engines to the database.

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# Realising the Data Hubs Concept for Urban Research in Australia

1. Phillip Delaney<sup>a\*</sup>
2. Chris Pettit<sup>a</sup>

**Abstract:** Discovering and accessing relevant data is a problem often faced by urban researchers, policy and decision-makers across Australia. To address this, several public, private and academic entities are establishing Data Hubs; online catalogues for data discovery, access and interrogation. Data Hubs are typically web services accessible via a portal, however often narrow geographic or application focus, and provide varied levels of analytical and visualisation capability. The Australian Urban Research Infrastructure Network (AURIN) is an initiative focused on providing urban researchers, policy and decision-makers better access to comprehensive datasets through a dedicated e-Infrastructure platform. The AURIN portal will facilitate programmatic access to data held in many emerging Data Hubs across Australia. AURIN is implementing a federated data approach, providing a single access point and common interface for interrogating datasets. This paper outlines the Data Hub concept, describing the process and benefits of Data Hub integration within the AURIN e-infrastructure context.

**Key words:** Data Hubs; Urban Research; e-Infrastructure; Open Data

## I. Introduction

In this paper will introduce the concept of data hubs as a mechanism to provide better access to urban researchers, policy and decision-makers in Australia to make evidence based policy. With the advent of the digital city, also referred to as the ubiquitous or smart city, there is a growing need for data to be more accessible and support evidence based decision-making<sup>1</sup>.

The Australian Urban Research Infrastructure Network (AURIN, <http://aurin.org.au/>) is building an e-infrastructure oriented to the needs of Australia's urban and built environment researchers. AURIN has been established to assist in better connecting researchers to data holdings across Australia. Data Hubs are considered an integral part of the AURIN e-infrastructure. In this paper we will discuss how AURIN is establishing a number of data hubs in a federated architecture to provide better access to Australia's growing digital urban data asset. The Melbourne Data Hub is presented as a case study. The paper concludes by discussing the

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<sup>a</sup> The Australian Urban Research Infrastructure Network (AURIN), University of Melbourne, VIC, 3052 Australia

<sup>\*</sup>Corresponding author, Phillip Delaney [pdelaney@crcsi.com.au](mailto:pdelaney@crcsi.com.au)  
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next steps in implementing series of federated Urban Data Hubs across Australia linked via the AURIN e-infrastructure and discusses some of the challenges and opportunities in doing so.

## **II. The Emergence of Data Hubs**

Data hubs have been created to address issues arising from the discovery, access, and format diversity of research data. A data hub can be visualised using a 'Hub-and-Spoke' architecture. Data is housed in a central system, or hub, with users accessing the data from many locations, or spokes. The Open Knowledge Foundation defines a data hub as 'a community-run catalogue of useful sets of data on the Internet', and notes that in addition to data searching, the data hub 'may also be able to store a copy of the data or host it in a database, and provide some basic visualisation tools'<sup>2</sup>. The scope and variety of applications of the data hub concept is very broad, but at the core a data hub needs to be a single access point that:

- Allows users to search for a variety of data;
- Allows users to access and use this data;
- Provides data in a discrete set of formats;
- Allows users/data custodians to contribute data to the hub; and
- Provides information about the data (metadata).

Data Hubs are a development of data warehouses, data marts and geoportal technology, and have been designed to allow users to discover, access and share data. However, the collaboration element is what clearly differentiates the data hub concept from the data warehouse and geoportal concepts. This collaboration has some clear benefits, and clearly addresses the issues of data discovery and access, and allows for a much more collaborative research environment. In addition, the data hub reduces duplication of data storage and creation by providing a single, online access point for data. Finally, allowing data to be consumed online from the data hub allows users and developers to develop customised products and services using these datasets<sup>3</sup>.

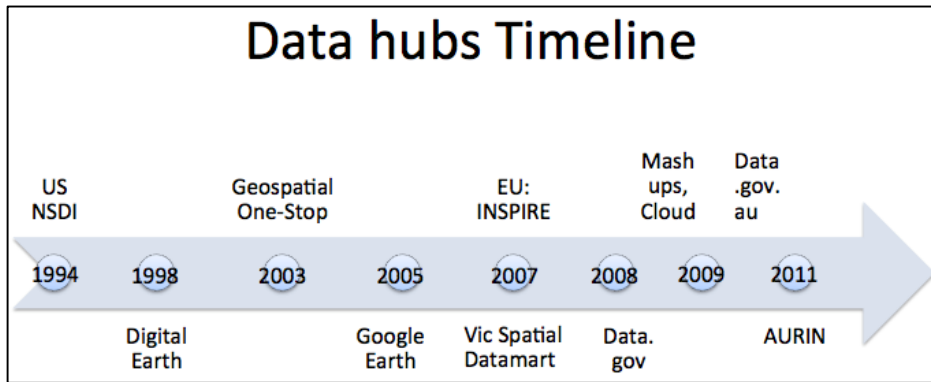
One of the main limitations of the data hub is that any downtime of the data infrastructure results in users losing access to data, without a redundant system for data access. This is an inherent risk in the consolidated data hub approach, one shared with data warehouses and geoportals<sup>4</sup>. However, continuous developments in the management of these systems have resulted in improved management methods, reduced down time and minimised impacts to users.

As a geoportal, AURIN's primary focus is to provide spatially explicit urban data and relevant analytical tools. Tait<sup>5</sup> describes a geoportal as 'a web site considered to be an entry point to geographic content on the web or, more simply, a web site where geographic content can be discovered'. These geoportals evolved from ongoing developments in Spatial Data Infrastructure (SDI), which were created by various national mapping agencies, like USGS, to manage their spatial information<sup>6</sup>. SDI were initially developed to manage and distribute data internally within related organisations, but have developed as broader technology for managing and distributing spatial information to various users and applications.

The data hub as a concept incorporates geoportals, but with the increasing focus on big data and open data distribution, the data hub concept has been applied to many fields and many types



of data. Large technology organisations such as Microsoft have invested heavily in developing enterprise level solutions to the data hub concept, with specific application development using SQL server to develop a ‘hub and spoke architecture’ solution to data storage and distribution<sup>7</sup>.



**Figure 12. Evolution of the Data Hubs (modified from [13])**

The advent of the data.gov open data movement in 2008 resulted in increasing volumes of data available and distributed to the public, and cloud computing allowed a new way to think about this storage and distribution<sup>8</sup>. The variety of options now available to store and distribute data led to the application of the data hub concept in several large-scale projects across the globe.

- **A. Data Hubs and International Initiatives**

The Data Hub concept has been realised to many locations and contexts globally. Many scientific fields have collaborated to create research specific data hubs to store, discover and distribute research data to other researchers. Examples of these hubs can be found in the fields of health, environmental and engineering research.

In the urban research community, the European Union (EU) has established the Urban Audit data hub as a collection of comparable city statistics across the EU, and the BPiE data hub to specifically collate open data on building stock and building policy. While there is an apparent paucity in specific urban data hubs, many federal and local government agencies have geoportals for the display and interrogation of urban data. In addition, much data relevant to the urban environment is being distributed through broad application data hubs.

Broad application data hubs are much more prevalent than research specific hubs, and have been set up to create a community of general knowledge sharing. They have the advantage of not being constrained by a particular type of dataset or field of interest, but can be more difficult to search, and contain less detailed information than the field specific hubs.

Initiatives such as [www.datahub.io](http://www.datahub.io) have been launched by the Open Knowledge Foundation (OKF) as a free data management and distribution system to allow any user or organization to host and distribute data. In addition OKF has released CKAN, an open source software solution for data publishers to use to create data hubs, making their data accessible for the public. Many government agencies across the world have taken advantage of this open data hub technology



(like the USA, Canada, UK, Germany or Mexico). In Australia, State Governments in Queensland and South Australia have initiated similar moves<sup>6</sup>. These data hubs form the technical basis for Open Government Data Initiatives around the world. Within this initiative, governments aspire to publishing unrefined or raw public datasets in an open, non-proprietary technical format, licensed for use, re-use and re-distribution at marginal or no cost<sup>9</sup>.

- **B. Data Hubs in Australia**

In July 2010 the Australian government released a Declaration of Open Government to promote an open government based on 'better access to and use of government held information, and sustained by the innovative use of technology'<sup>10</sup>. One of the primary benefits behind the open government initiative is the broad scale release of government information, including many data sets held by both commonwealth and state government bodies. To distribute this information, the Australian Federal Department of Finance and Deregulation has established <http://data.gov.au/>, a broad scale data hub for discovery and access to government data based on the OKF CKAN platform. This site distributes hundreds of datasets from 120 different contributing government organisations. State governments in New South Wales, Queensland, South Australia, Victoria and the Australian Capital Territory have also released similar open data policies, and are all on the way to providing searchable data.gov.au data hub sites<sup>12</sup>. In Victoria, this policy has also lead to the release of many GIS datasets through both direct download and through a machine-to-machine data hub hosted by the Department of Environment and Primary Industries.

Other notable data hubs which have been established within Australia include the University of Wollongong SMART Infrastructure Dashboard (<http://smart.uow.edu.au/projects/UOW145700.html>), Western Australia's Landgate SLIP and SLIP Future projects (<https://www2.landgate.wa.gov.au/web/guest/home>), and PSMA data services (<http://www.psma.com.au/?product=psma-systems>).

AURIN has been established as a dedicated urban data hub in Australia, and AURIN aims to use the data hub concept to facilitate machine-to-machine access to datasets across the country held by key national, state and local government agencies, and private sector organisations. AURIN leverages both the data hub hosting and distribution features to access data at the source, and consume the data within the AURIN portal. This ensures that the AURIN portal is accessing the most up to date information within the data hub, allowing users to have increased confidence in the data from the portal. The AURIN portal will also allow users to contribute their research outcomes back in to the portal for other researchers to discover and use for their research purposes, aligning with the collaborative aims of the data hub concept.

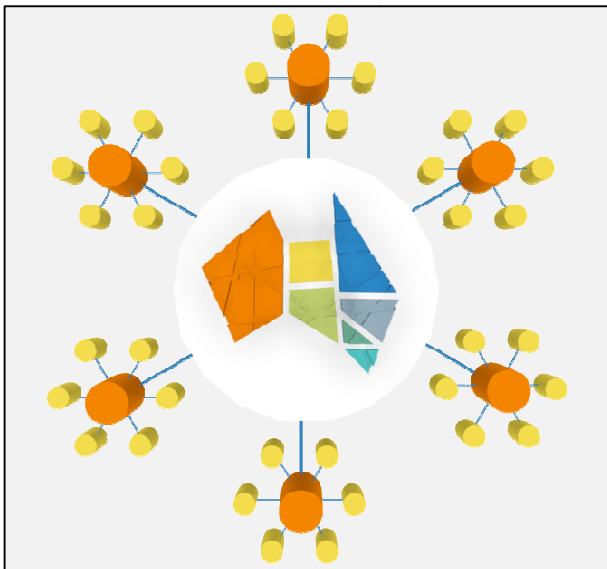
While the definition of a data hub can clearly be quite broad, for AURIN purposes, data hubs need to align with the criteria below. Reduced down to the key components, these an AURIN data hub needs to focus on collaboration, standards, and federated, programmatic data access:

- Provides programmatic access (machine to machine access) to a number of data services.
- Aligns to a federated data service model and support data interoperability so that other portals web mapping tools can build off the hub.

- Aligns with a data/metadata standard-driven approach where possible (for example SDMX, ISO19115).
- Has a consolidated level of technical operational support at the designed hub.
- Encourages a collaboration and consortium approach.
- Realises economies of scale through multiple data feeds and external partner support relating.
- Leveraging existing data services infrastructure where possible.
- Facilitates licensing arrangements with data custodians through relevant government department or agency.

AURIN aims to connect to many hubs, along the ‘spokes’, and make the data in these hubs available for discovery, analysis and download. In this way, the AURIN portal can be visualized as a hub of hubs – a single access point allowing users to access and combine information from hubs in different geographic locations and from different specialist themes. This concept is highlighted in Figure 2. AURIN is currently exploring incorporating up to 12 data hubs across Australia. The first of these hubs to be integrated is the North West Melbourne Data Hub, explored in a case study below.

**Figure 13 – Contextual map of the AURIN data hubs**



- **C. Melbourne Data Hub Case Study**

Recognising the significant challenges that population growth will have on the liveability, the North West Melbourne Regional Management Forum (NWM – RMF) has identified the need to work collaboratively across government, academia to develop an integrated spatial data platform to support research in the region<sup>13</sup>.

The North West Melbourne Data Integration project included members from 14 local government authorities as well as AURIN and ANDS to use web enabled technology to connect

computers, exchange data and undertake analysis. The key component of the NWM project was the ability to access and distribute spatial datasets to various project stakeholders. This was achieved these through the creation of the Melbourne Data Hub, which made an extensive range of health, housing, transport and planning datasets available to users both to contributing agencies and to urban research across Australia via the AURIN portal<sup>14</sup>.

The data hub was established and maintained by the Centre for Spatial Data Infrastructure and Land Administration (CSDILA), and consisted of two main components: a server to distribute the datasets and a tool to harvest and enrich metadata for each dataset. The data was distributed using GeoServer Web Feature Service (WFS), which is an open source geospatial data server. CSDILA collaborated with several government agencies to collate urban data, then clean and geocode many of the supplied datasets which were not in a suitable format for distribution. These datasets were then imported to a PostGIS database for distribution through the GeoServer. A second GeoServer was also used for the project, housed at the Department of Environment and Primary Industries. This GeoServer was used to distribute data which was already held within the Victorian Spatial Datamart<sup>14</sup>.

To bring these WFS feeds in to the AURIN portal, CSDILA also created a metadata harvesting and enrichment tool using GeoNetwork as the basis, with custom metadata requirements built in to meet the AURIN specifications. This tool was used to capture and enhance title, dataset abstract and attribute abstract information for each of the datasets before being ingested in to AURIN. This allowed the data to be consumed by AURIN with fully compliant metadata, allowing users to understand each component of the datasets.

The data hub was also used to serve various datasets to four demonstrator projects, which were used to demonstrate the value and utility of the NWM data hub in the urban research areas of Health, Housing, Walkability and Employment. The data hub was fundamental in consolidating and distributing datasets for various research application purposes. Each of the four demonstrator projects successfully used the data distributed from the data hub. At the project completion, the NWM data hub was distributing more than 120 datasets through the AURIN portal, from more than 10 contributing government agencies within Victoria, all with fully compliant AURIN metadata<sup>8</sup>. <http://blogs.unimelb.edu.au/aurinands/>

### **III. Conclusion**

The application of the data hub concept in Australian increases the ease of data discovery and access. By incorporating this concept in to the AURIN portal, it will also allow researchers to collaborate on research and share the outcomes to the urban research community. The success of the North West Melbourne Data Hub illustrates the benefits that can be gained from a consolidated data hub for many areas of urban research. As such it is recommended that AURIN pursue the data hub concept as the means of enabling collaborative, innovative urban research applications to support urban development and design in Australia.

Data Hubs provide many opportunities for Australia and internationally in enabling a collaborative research environment. However, there are several challenges still to be faced in

broad scale implementation of the data hub concept, including distributing and consuming live data feeds and crowd sourced data, simplifying in public and private data licensing, enabling access to a wider variety of data formats, and enabling more efficient incorporation of open government data.

A key step for developing the data hub concept will be to develop a common framework for establishing data hub infrastructure. This will increase the interoperability of data hubs and which will support future research applications. In addition, data hub developers will need to ensure they are promoting the use of their infrastructure, and capturing user stories to highlight the benefits of the data hub concepts. Addressing these opportunities will maximise the use, collaboration and volume of data provided through data hubs.

### Acknowledgements

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# Data-Driven Forecasts of Regional Demand for Infrastructure Services

Jun Ma<sup>a</sup>  
Rohan Wickramasuriya<sup>a</sup>  
Pascal Perez<sup>a</sup>  
Murad Safadi<sup>a</sup>

**Abstract:** The socio-economic development and liveability of a region are affected to a great extent by the region's infrastructure services. Data-driven forecasting the demands for infrastructure utilities (for example, electricity, water, and waste) of a region becomes a challenging issue in the situation of highly integrative infrastructure networks and restricted data sharing, which involves handling temporary and spatial infrastructure utility data simultaneously and modelling the correlations between different infrastructure utilities and their interactions with relevant socio-economic and environmental indicators. Data mining and complex fuzzy set techniques are used to implement this kind of analytical capability in SMART Infrastructure Dashboard (SID). The developed forecasting method and technique can be used by local governmental agencies, infrastructure service designers and providers, and local communities for better governance, planning and delivering of effective and efficient infrastructure service and facility. It can also provide support evidence for a region's long-term sustainable planning and development.

**Key words:** Forecast; Infrastructure Services; Data mining; Fuzzy sets.

## I. Introduction

Providing efficient and effective infrastructure services to local communities of a region is the base of improving its residential liveability, attracting commercial and industrial investments, advancing multi-cultural perspectives, and maintaining long-term sustainable development. To achieve this goal, an appropriate forecasting of regional demand of infrastructure services is a critical step<sup>1-2</sup>, which needs to consider not only provision of various infrastructure utilities and facilities but also the correlations among these infrastructure services and other relevant socio-economic, demographic, cultural, as well as environmental factors<sup>3</sup>. All sectors related to regional infrastructure services have produced huge amount of data, developing an appropriate data-driven forecasting of infrastructure service demands can benefit the local governmental agencies, infrastructure services planners, designers, and providers, local residences, and

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, NSW 2522, Australia.

\*Corresponding author: Jun Ma [jma@uow.edu.au](mailto:jma@uow.edu.au)  
<http://dx.doi.org/10.14453/isngi2013.proc.30>

infrastructure researchers for better administration, development, use and understanding interactions between human behaviours, climate changes, and public services.

In this work, we introduce the practice of developing and employing a data-driven forecasting model of regional infrastructure service demands in the SMART Infrastructure Dashboard (SID) project being developed by the SMART Infrastructure Facility, the University of Wollongong. SID tries to provide support for regional infrastructure development through three integrated platforms, namely an information platform, an analysis platform, and a decision making platform. The data-driven forecasting model is one of functionalities provided by SID.

## **II. Data-Driven Forecasting Challenges**

Developing a data-driven forecasting model of regional infrastructure service demands will provide challenges from data processing, data modelling and data visualisation. Data is the key to conducting forecasting of regional infrastructure service demands. Relevant data covers but is not limited to infrastructure utilities and facilities (such as electricity, water, and gas supply, waste collection, transportation, telecommunication and internet/wireless services), local area demographic characteristics (such as dwelling structures, population densities, population compositions), local socio-economic indicators (for examples, industrial structures, recreation traditions), and environmental measures (for examples, precipitation, temperatures, vegetation, geological structure and hazards). During long-term infrastructure development and practices, public service agencies, private providers and other infrastructure service related entities have accumulated mountains of infrastructure service data; however, these data are held separately or owned by individual entities due to all kinds of restrictions, policies and agreements. Data sharing is difficult and even prohibited. Although it has become an urgent requirement in infrastructure service communities, developing a data-driven forecasting model is far behind the needs of practitioners and commuters. Moreover, a data-driven forecasting model also needs to face challenges in data feature comprehension and data quality regulation. In practice, it is unlikely to use perfect data without missing values and uncertainties.

Modelling techniques and methods are also challenges faced in a data-driven forecasting model. Data modelling is the foundation of forecasting demands of regional infrastructure services. Data mining, statistics, and machine learning techniques and methods have been widely used in building forecast models<sup>4-6</sup>. Existing modelling techniques and methods may not suit infrastructure practices. For instance, these modelling techniques and methods particularly focus on structured data, such as number, text, image, video, audio; however, infrastructure services data has greater emphasis on unstructured data, such as geographic distribution, interaction between different services. Hence, new modelling techniques and methods need to be investigated combining existing techniques and methods with infrastructure services features.

Data visualisation is an easily and commonly ignored challenge in a data-driven forecasting model<sup>7</sup>. Data visualisation is not new - a simple scatter chart of a data set can be seen as a simple data visualisation. Data visualisation is an intuitionistic and effective way to reveal the inner patterns and trends hidden in the data. Data of infrastructure services has particular spatial and temporal features. For example, infrastructure utility consumptions change from place to place and from season to season. It is hard to demonstrate a forecasting model without considering these features in infrastructure service area. Using data visualisation techniques in a forecasting

model can provide an intuitionistic and dynamic view of the changes of infrastructure service related factors and their interactions. Dashboard is an appropriate tool to implement data visualisation for infrastructure services. Recently, single infrastructure service dashboards have been developed; however, no cross-infrastructure service dashboard has been reported. SID tries to provide such one.

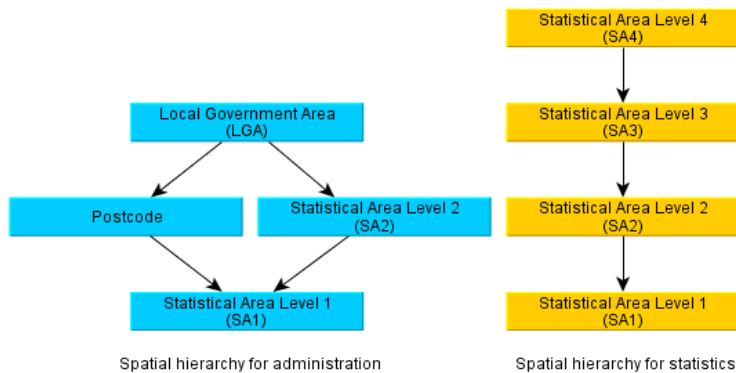
Combining data processing, data modelling, and data visualisation techniques, SMART Infrastructure Facility is developing a data-driven forecasting model of regional demands of infrastructure services in SID.

### III. Data-Driven Forecasting (DDF) of Demands of Regional Infrastructure Services

The DDF focuses on the Illawarra region, NSW, Australia, which is a coastal area, south of the Greater Sydney Metropolitan Area. Traditionally, the region covers five local government areas (LGAs) – Wollongong, Shellharbour, Shoalhaven, Kiama, and Wingecarribee. Due to the fact that the Australian Bureau of Statistics (ABS) adopted a new geographic classification standard in its 2011 and will use it in its following censuses, the region boundary used in this paper is following the ABS 2006 census but the data is aligned to the ABS 2011 geographic classification hierarchy for future extension.

The data collected for the DDF includes electricity consumptions, water consumptions, regional temperature and rainfall measures, regional demographic profiles (such as population, dwelling types and compositions, household and family incomes, household and family compositions), community travel surveys and statistics.

The collected data is also dispersed in different spatial and temporal scales, aggregation and disaggregation methods are used to regulate the data to a given spatial and temporal metric according to the application requirement. Generally, two main spatial hierarchies are used in the DDF (see Figure 1). The DDF adopts three main temporal scales, namely, ‘yearly’, ‘seasonal (quarterly)’, ‘monthly’. These scales are based on the analysis of the common data collecting periods.



**Figure 1. Spatial hierarchies for DDF.**



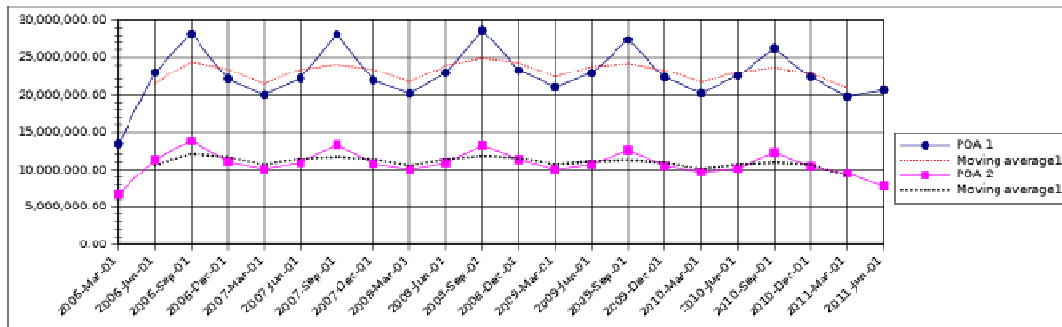
The DDF adopts existing methods from data mining, machine learning, statistics and other relevant research areas. It also creates new methods according to the specific requirements and special features of infrastructure service data. For examples, fuzzy sets and complex fuzzy sets techniques have been used to describe the uncertainty and the seasonal features in infrastructure utility consumption; and classification and clustering techniques are used to extract correlations between different kind of infrastructure services and between infrastructure service, demography profiles and environmental indicators. These methods will be stored as stored in a repository for future revision and usage.

The outcomes of the DDF will be visualised through corresponding SID reports. Users thus can obtain the integrated and dynamic views of the interested information of demand of infrastructure services including its changes along a timeline and its trends in the future under the impacts of relevant factors.

#### IV. Case Study: Residential Electricity Consumption at Postcode Level

This section describes the DDF through an example of forecasting residential electricity consumption. For simplification, we take ‘postcode-seasonal’ as the focused spatial-temporal scale.

Electricity is an important infrastructure utility. The demands of residential electricity have clear seasonal feature (as shown in Figure 2). At the same time, they are affected by residential characteristics and environment factors. In order to investigate the demands of residential electricity, we collected relevant data and conducted the DDF.



**Figure 2: Comparison of residential electricity consumptions in two postcode areas (POAs).**

The data collected for this study includes monthly rainfall and temperature records, population, ratios of different dwelling structures (separated house, semi-detached dwelling, flats or units), household median incomes, and seasonal electricity consumptions at census collection district (CCD) level (the smallest statistical unit in geographic classification in the ABS 2006 census) in five years from 2006 to 2011.

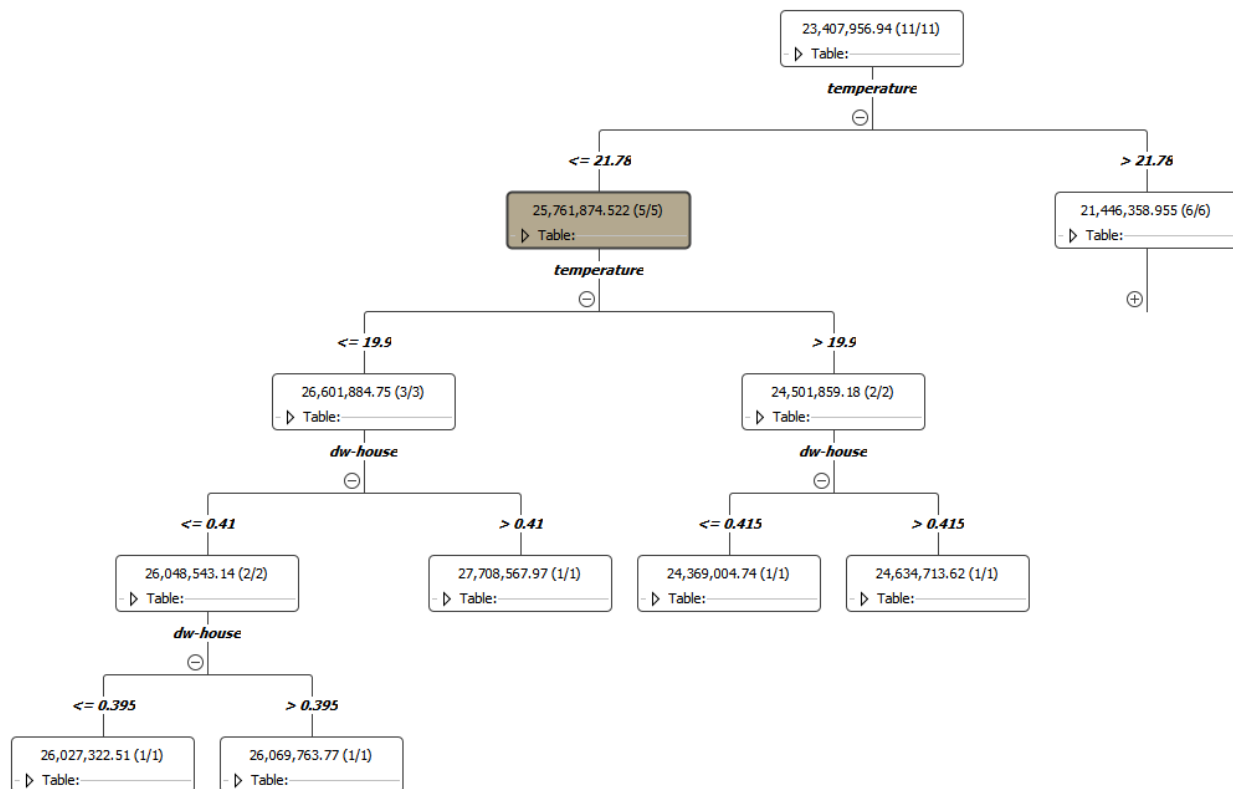
The obtained dataset is incomplete and contains many missing values and uncertainties. Main features of the data include:

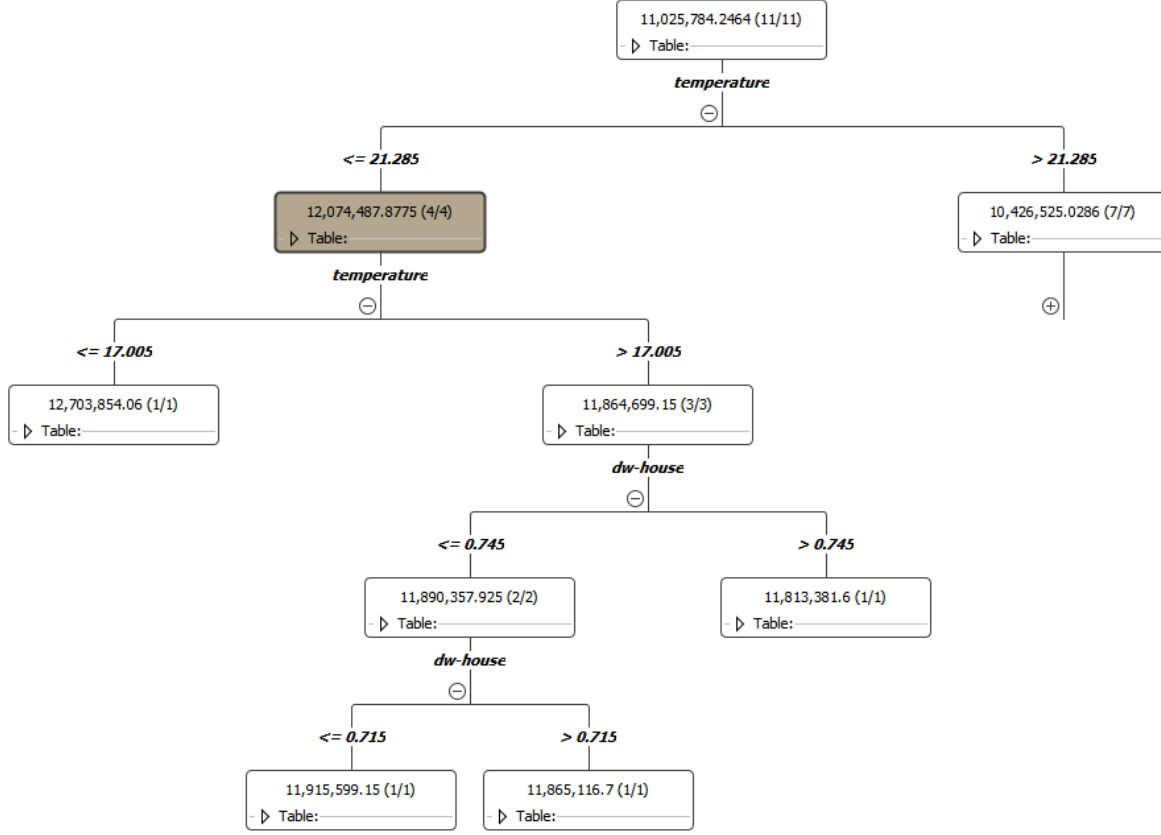
- Rainfall and temperature data is collected from meteorological stations at specific locations.
- Population, dwelling statistics, household median incomes are only available for census years.
- Rainfall and electricity data are accumulated data which with time lags.

Considering these features, some geospatial information processing techniques and interpolation methods are used to convert and transform the raw dataset to the given ‘postcode-seasonal’ scale. These techniques and methods include:

- Kirging technique is used to generate postcode level rainfall and temperature measures.
- Linear interpolation is used to generate seasonal population, dwelling statistics, household median incomes in non-census year.
- Fuzzy sets and complex fuzzy sets<sup>8-9</sup> are used to describe the uncertainties in the rainfall and electricity consumption data.

After the necessary data pre-processing, a complete dataset is available for the DDF. Existing and developed software packages are applied to generate forecasting models. These models can be various forms such as neural networks, decision trees, logit models, as well as statistical models. Figure 3 shows two sections of decision tree models of residential electricity demands for the two postcode areas. The models are generated using the *KNIME* software.





(a) Postcode area 1

(b) Postcode area 2

**Figure 3. Sections of decision tree forecasting models of residential electricity demands in two postcode areas.**

## V. Conclusion and Future Work

Forecasting the demands of regional infrastructure services has significant impact on better decision in infrastructure management, planning and designing. Data-driven forecasting is always an effective way to provide evidenced support for infrastructure development, particularly in today's big-data era. Provision of a data-driven forecast needs to overcome various barriers and challenges in data sharing and data modelling.

The SMART Infrastructure Facility is conducting relevant practice in its SID project which aims to provide regional infrastructure services information platform, analysis platform and decision platform. This paper briefly introduced the initial practice we have conducted in the project. To achieve the planned aims of the SID project, more works still need to be studied further such as forecasting techniques and methods, infrastructure services data understanding and processing.

## Acknowledgments

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# Action in 8 Domains for an 8 Factor Improvement: Infrastructure with Agency

L. Varga <sup>a</sup>

**Abstract:** “Infrastructure with agency” embraces both the physical assets for extraction, production, distribution, and storage of utilities, and infrastructure use for the purpose of trade, business and societal well-being. The micro-level interactions of infrastructure use lead to macro-level structures and patterns which satisfy demand and determine the value of infrastructure to users. Interactions generate and are generated by non-linearities and feedbacks within the various integrated systems and provide a source for exponential growth. This article considers how interactions between Infrastructure, utility businesses, users and consumers, and the government can enable co-evolutionary exponential growth. Eight specific recommendations are made to address an eight factor demand growth. The fruitfulness of these recommendations is impossible to predict because the system is complex, that is evolutionary and adaptive, and depends on future contexts, not least, technologies we cannot imagine today.

## I. Introduction

If we define “critical infrastructure” as “infrastructure with agency” then we embrace both its physical assets for extraction, production, distribution, and storage of utilities<sup>1</sup> and its use for the purpose of trade, business and societal well-being. ‘Infrastructure with agency’ highlights the focus of behaviours between infrastructure agents, utility business agents and consumer agents. This is akin to the co-evolution of physical technologies, business designs and social technologies respectively<sup>2</sup> as described in *The Origin of Wealth*<sup>3</sup>. The thesis suggested in this paper is that the co-evolution of these systems, and thus the potential for non-linearity and positive feedback, is a key opportunity for exponential growth.

With three broad groups of agents, co-evolution can occur in six ways: co-evolution within each system, and co-evolution between each system. Opportunities for co-evolutionary change in the context of government give rise to a further three opportunities. These are depicted in Figure 1. The remainder of this paper discusses the prime recommendation for each co-evolutionary relationship.

## II. Infrastructure Coevolution (1)

A useful conceptualization of the components and structure of any infrastructure system is the conversion points’ ontology<sup>3</sup> which describes assets at any scale. It uniquely defines assets by geographical attributes, but importantly identifies all utility resources consumed by the asset, in the relevant proportions; the resources generated, including waste; the technologies used, and

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<sup>a</sup> Director, Complex Systems Research Centre, Cranfield University, Bedford, UK  
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related efficiencies and materials use; and the policies and mechanisms in force, constraining or enabling the adoption of the asset. Interdependencies in a landscape of conversion points can be identified by looking for the presence of conversion points with similar attributes: 1. the same resources used: identifies resource interdependency, 2. the same policies: identifies governance interdependency, 3. the same technologies: identifies technological interdependency (and potential for technological efficiency improvement), 4. the same geographical coordinates: identifies locational interdependency. Vulnerabilities in the infrastructure can be determined using principles of network theory upon a conversion points' model of the infrastructure.

A way to solve some of the interdependency issues of infrastructure is to create fungible conversion points. Such points can be configured to play a role in one system or another, but may not play both roles simultaneously. For example, batteries in electric vehicles could be used to for electricity grid support<sup>4</sup> when not providing mobility. This is in contrast to dual roles of infrastructure, such as water reservoirs which deliver flood mitigation and urban water supply concurrently, which create lock-in and compromise the water supplier's ability to trade<sup>5</sup>. In addition, novel uses of the infrastructure, novel combinations of infrastructure assets, new instances of assets, or innovation of new technologies, give rise to potential multi-factor improvements.

Recommendation 1. Use infrastructure for fungible purposes to improve security and resilience.

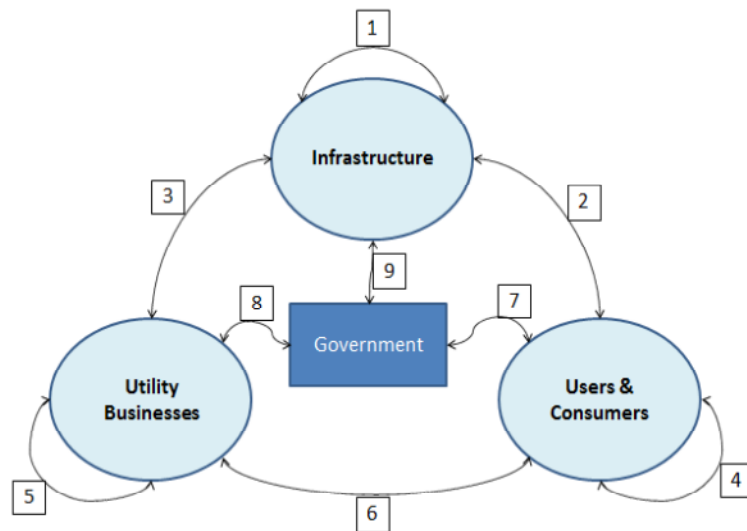


Figure 1 Coevolution of Infrastructure Systems

### III. Coevolution between Infrastructure and Users (2)

The operational flows of resources, such as water, power, waste, vehicles, and communications, are processed continuously in order to balance supply with demand. But additional physical flows are often available in step changes, for example, another power plant,

water treatment works or HGV. At different times there will also be under-utilization of different parts of the infrastructure as well as demand beyond the available capacity. How can utilization be improved? How can losses be avoided? What technologies can be used to improve utilization, for example, how can freight vehicles avoid empty running? What technologies are needed to improve efficiencies (and when will they be innovated and tested)?

Recommendation 2: Identify and resolve under-utilization and poor efficiencies, in order to remove avoidable inefficiencies.

#### **IV. Coevolution between Utilities (Businesses) and Infrastructure (3)**

The value of infrastructure is different for different groups and is not reflected accurately in traditional accounting discounted prices, particularly when assets are in use beyond their planned life-times, which is significant for much of the transport and water infrastructure in the UK. A pragmatic approach is to evaluate infrastructure based on the current annual cost of avoiding asset replacement. This approach would need to be pluralistic and take into account the value provided by the system (not just the single asset), the latest technological alternatives for replacement, and the environmental and resource costs of replacement.

Recommendation 3: Assess the value of infrastructure by the costs it avoids in order to improve investment decision making and to reflect pluralistic views and technological alternatives.

#### **V. User Coevolution (4)**

If users are able and motivated to invest in their own utility generation or works, such as photovoltaic cells, rain-water harvesting, electric vehicles, then as adopters they can acquire skills which can be shared with other users. These users also provide a means of marketing technologies and behaviours for local use usually involving renewable resources. Other users and consumers are influenced by the community networks to which they belong. These practices can avoid demands upon infrastructure and create local security of supply. A recommendation is not made in respect of social networks as they are self-organising.

#### **VI. Utilities (Businesses) Coevolution (5)**

Utilities are focused on single industries, such as power, water, or transport. Whilst usually vertically integrated, they do not collaborate with other utility providers although improvements in one utility can often create greater demand for other utilities which can create worsened systemic effects. Sales are driven by the notion that more is good although the provision of more can lead to step changes in demand provision which are then under-utilized and affect consumer prices. A shift in focus to services and not utilities, e.g. not water and energy, but ambient heating/cooling, would create an improvement in understanding the need for more utilities.

This focus on services would require utilities to work differently, for example, through joint ventures at local government level. A multi-utility service perspective would enable regulation to aim at the real benefits of public services. A service perspective would also lead to long term relationships between utilities (and consumers) and create a better focus on sustainability. For example, Energy Service Companies (ESCOs) implement various energy service business models, which benefit the user through the implementation of energy efficient technologies<sup>6</sup>.

Recommendation 4: Design and create inter-utility solutions service provisions by incentivising inter-utility relations which are beneficial to infrastructure sustainability.

## **VII. Coevolution between Utilities (Businesses) and Users (6)**

Consumer pricing for utility products needs to reflect utility business costs and the costs of the infrastructure they own or use. Extant consumer pricing strategies are often difficult to fathom and usually encourage excessive use, as the lowest prices are charged for highest consumption. New pricing strategies are needed which encourage limited consumption focused on penalizing excessive consumption. For example, a pricing strategy akin to the tax code system would discourage excess use: there would be a free amount of energy, becoming progressively more expensive.

Recommendation 5: Focus on service need rather than unconstrained demand by actively discouraging excessive use of services.

## **VIII. Coevolution between Users (Consumers) and Infrastructure (7)**

The most significant costs in utilities arise due to oscillations in demand. Flattening demand to make it more predictable will reduce costs. For example, in energy systems, stable demand flattening through smart grid solutions is achievable using smart energy control and communication devices in contrast to traditional methods using wholesale price signals<sup>7</sup>. These methods are new however practical changes are evident globally as we observe domestic, industrial and commercial consumers producing their own utility products and services, such as rain water harvesting, or solar heating, through the use of micro-scale technologies, and sometimes incentivised by government policy. Many small-scale changes will lead to changing demand patterns on national infrastructure. However these solutions will create more oscillations in demand unless technology for storage is innovated at the same speed as renewable energy generation.

Recommendation 6: Make the user and consumer a part of the system and not an exogenous factor by supporting local schemes to capture renewable resources and produce utility products which reduce demand upon aging infrastructure.

## **IX. Coevolution between Government and Utilities (Businesses) (8)**

Infrastructure needs commissioning, building, operating and decommissioning. Various agencies are involved, including the state for political leadership and regulation, engineering



companies, local government for planning and control, materials and resources suppliers, system operators and distribution network operators (for water and energy). The cost of each agency has a bearing on the competence of national infrastructure. How competent is each agency: how effective are its interactions with other agencies? What avoidable barriers are there? Does each agency take appropriate responsibility for security, economics and waste? Is each agency considering integrated improvements in various time dimensions (short, medium and long)? The competence of national infrastructure has potential for improvement at various scales: local, municipal, inter-city, and city.

Recommendation 7: Continuously evaluate the competence of national infrastructure in order to resolve inter-agency barriers and to focus on the competence of national infrastructure as a whole system.

## **X. Coevolution between government and infrastructure (9)**

It is a very complicated problem to decide which components of infrastructure needs development (and when) for the good of society and the maintenance of GDP. Infrastructure exists at many scales, it may not be located where demand is greatest and it is limited by the technologies used. We can be certain that diversity is needed to provide resilience and opportunities for future pathways, and that the on-going consideration which is needed for prioritization must take into account all utility services. For example, we cannot invest in programmes as significant as HS2 without considering alternatives and parallels such as fast broadband<sup>8</sup>. In the UK's privatised utilities' industry (e.g. the energy industry<sup>9</sup>) central government leadership on national projects is a political matter and led by Infrastructure UK, part of HM Treasury who have delivered a long-term plan<sup>10</sup>. The role of the Independent Infrastructure Planning Commission (IPC) in examining applications for "nationally significant infrastructure projects" moved in 2012 to the Planning Inspectorate, an executive agency of the Department for Communities and Local Government (DCLG), following the 2011 Localism Act. However, local and environmental objections to national plans (for example, Channel Tunnel, HS2) appear to be resolved through the creation of hybrid bills which are Acts of Parliament<sup>11</sup>.

The need for balance between local (municipal) and national (or federal) needs is critical to sustainability. Bankruptcies of municipalities in the US (see Detroit's Chapter 9 statement<sup>12</sup>) are examples of unaffordable debt where local authorities have invested in infrastructure but cannot raise enough revenue (typically through local taxation) to meet repayments and provide on-going quality services. Populations dwindle and the problem becomes intractable. The challenge of investment is the belief that hardship today (high taxes typically) brings rewards (lower cost of services, more services) tomorrow, but individuals' self-interest can wane waiting for the long-term (usually around a generation). Nevertheless free trade and social well-being depend upon infrastructure and so cannot be left to political and thereby short-term decision making. Introducing an apolitical non-governmental body financed by both the Treasury and business, and answerable to social need, is essential for long-term sustainability.

Recommendation 8: Create an interdisciplinary agency to lead national infrastructure strategy thereby creating a long-term plan and benefits realisation programme funded by government and business for the good of the nation.

## **XI. Conclusion**

A co-evolutionary systems perspective is taken in this paper to identify opportunities to resolve the factor 8 problem in critical infrastructure. The recommendations provided in this paper recognize the significance of agency in these systems and highlight the choices for these agencies to change behaviours. Some utilities have specific problems such as the energy 'trilemma' — how to consistently provide affordable energy services, achieve security of energy supplies and reduce greenhouse gas emissions from energy conversions to mitigate climate change<sup>13</sup> whereas the problems for other utilities are not so clearly defined. The recommendations suggested above reflect the learning gained from a number of critical infrastructure research projects in the last five years. Some recommendations will be fruitful beyond expectations, whereas others may have perverse effects. This is the nature of complex systems in operation. It is only through experimentation that feedback and rebound effects can be observed. In summary, these recommendations are:

- Recommendation 1: Use infrastructure for fungible purposes
- Recommendation 2: Identify and resolve under-utilization and poor efficiencies
- Recommendation 3: Assess the value of infrastructure by the costs it avoids
- Recommendation 4: Design and create inter-utility solutions service provisions
- Recommendation 5: Focus on service need rather than unconstrained demand
- Recommendation 6: Make the user and consumer a part of the system
- Recommendation 7: Continuously evaluate the competence of national infrastructure
- Recommendation 8: Create an interdisciplinary agency to lead national infrastructure strategy

Utility systems are highly dependent on technologies and so I leave the reader with a final thought on the possibilities that technologies hold. Two revolutionary technological daydreams are contained in Arthur C Clarke's afterword in the greatest engineering achievements of the 20th century<sup>14</sup>. The first is a material lighter and stronger than any metal which would enable a space elevator. The second is low-energy nuclear reactions with claims to produce ten times the energy it consumes. With supportive agent behaviours in government, infrastructure, utility businesses and consumers, these technologies alone would go a long way to address the factor 8 issue.

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# SMART Infrastructure Dashboard: A Fusion between Business Intelligence and Geographic Information Systems

Rohan Wickramasuriya<sup>a\*</sup>  
Jun Ma<sup>a</sup>  
Vivek Somashekar<sup>a</sup>  
Pascal Perez<sup>a</sup>  
Matthew Berryman<sup>a</sup>

**Abstract:** Business Intelligence (BI) has popularly been adopted as a process that enables easy access, analysis and visualization of information through specialized set of tools for informed decision making. Two most noticeable characteristics of traditional BI is that it (a) is largely used in single-organization environments and (b) uses predominantly aspatial data. We believe that BI has applications beyond single-organization environments, but it very much requires integration of geospatial capabilities given the increasing availability of large volumes of spatial data and a growing interest to see things spatial. The SMART Infrastructure Dashboard (SID), our innovative solution that fuses BI and Geographic Information Systems (GIS), fills this significant gap. In this study, we demonstrate how SID can be used to perform spatio-temporal analysis and visualization of diverse sets of data to uncover complex interrelationships among utility usage, demographics and weather patterns at local and regional scale.

**Key words:** Business intelligence; Geographic information systems; Infrastructure

## I. Introduction

Business Intelligence (BI) refers to ‘the applications, infrastructure and tools, and best practices that enable access to and analysis of information to improve and optimize decisions and performance’<sup>1</sup>. In terms of processes, a BI project involves data acquisition, data warehousing, data analysis and mining, and reporting and presentation<sup>2</sup>. Geospatial BI (Geo-BI) is an improvement upon traditional BI made possible by integrating Geographic Information Systems (GIS) with BI<sup>3</sup>. This integration, though technically challenging, opens up a myriad of new and exciting ways to analyse and present data. Given that the majority of data collected by

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, NSW 2522, Australia,

<sup>\*</sup>Corresponding author: Rohan Wickramasuriya [rohan@uow.edu.au](mailto:rohan@uow.edu.au)  
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organizations has a geographic reference<sup>4</sup>, Geo-BI provides the spatial perspective which was missing in traditional BI.

Though BI and Geo-BI are traditionally used in single organization environments primarily as a decision support tool that helps to achieve increased profits, we suggest that Geo-BI in particular has applications beyond this traditional use. In this study, we demonstrate how Geo-BI can be tailored to provide an integrated view on infrastructure networks and services for better governance and planning of cities and regions.

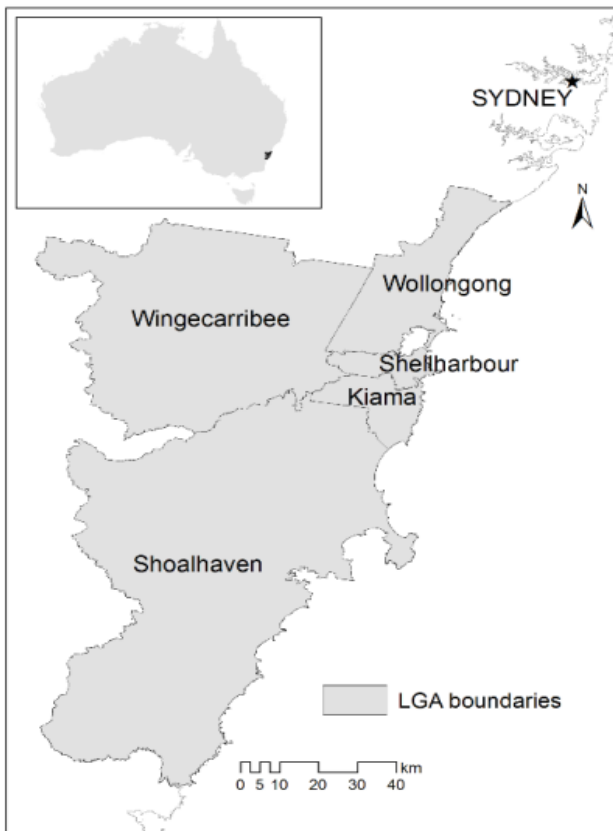
The Provision of infrastructure services to communities is a fundamental requirement, and this has been customarily viewed as the responsibility of governments at various levels. However, in many developed countries, including Australia, the private sector is increasingly dominating the provision of such services<sup>5</sup>. While this increasing private sector involvement eases the pressure on local and state governments' limited resources, it inevitably brings new challenges in terms of monitoring and regulating services provided by several disjointed organizations. These challenges are further exacerbated by the fact that modern infrastructure networks are highly interconnected<sup>6</sup>. Hence, local and state governments urgently need tools that can provide an integrated view on infrastructure networks and services. Such tools should overcome several technical challenges. First, given the diversity of infrastructure networks and the decentralized nature of their management, they should be able to harness diverse and dispersed data sources. Second, they have to handle the underlying complexity of operations on individual networks, as well as the interconnectedness of networks. Moreover, as any other decision-support system, these tools need to exhibit positive usability traits such as performance, user-friendliness and intuitive visuals.

The aim of this study is to develop a robust, easily accessible and user-friendly Geo-BI solution, the SMART Infrastructure Dashboard (SID), which can harness diverse and dispersed datasets to support decision making related to local governance of infrastructure services. SID aims to inform planners and policy makers about the current and past states of infrastructure systems and services, as well as their spatial and temporal interdependencies. SID also enables future planning by allowing users to run various 'what-if' scenarios based on user-defined parameter values. The current version of SID includes the following utilities: electricity and water distribution, as well as sewage and solid waste collection and treatment. SID has been principally designed for the Illawarra region in New South Wales, Australia.

## **II. The Illawarra Region**

The Illawarra, a coastal region located south of Sydney, is made of five Local Government Areas (LGAs): Wollongong, Shellharbour, Kiama, Shoalhaven and Wingecarribee (Figure 1). The first four LGAs occupy the coastal plain limited on the east by a forested cliff, while Wingecarribee LGA spreads across the southern tableland, west of the cliff. According to the 2011 census<sup>7</sup>, the population of the Illawarra region stood at 413,216 persons, 46.6% of which lived in Wollongong LGA only<sup>8</sup>.

Although the geography and topography of the Illawarra region have helped to create clear delineations for each utility network relatively well separated from neighbouring regions, authority and management vary considerably across utilities and jurisdictions. For example, the electricity distribution network is managed by a single operator (Endeavour Energy) for the whole region while water distribution is split between a private operator (Sydney Water, servicing Wollongong, Shellharbour and Kiama LGAs) and two local agencies (Wingecarribee and Shoalhaven LGAs). Likewise, a single private operator (REMONDIS) manages solid waste collection in Wollongong and Shellharbour LGAs while the three other LGAs administer their own facilities.



**Figure 14. The Illawarra regions, New South Wales, Australia**

### **III. Smart Infrastructure Dashboard**

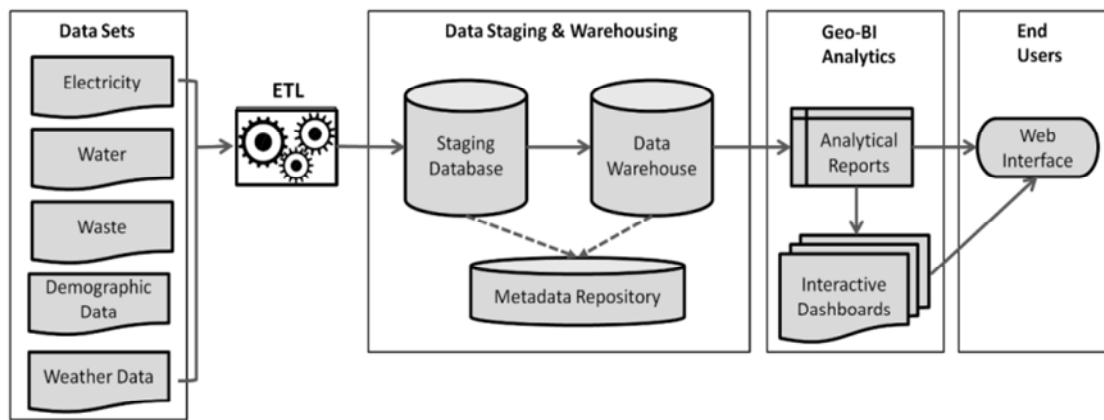
#### **A. Stakeholder and Data Types**

We identified the five LGAs and aforementioned private operators as stakeholders in the SID project. From SID's perspective, these stakeholders were both data providers and users. We collected a diverse set of data from them including geometric datasets of utility networks, service usage or consumption at various geographic levels over various time periods, water discharge at reservoirs and pumps, water quality at various points in the network, power consumption of

assets such as treatment plants and pumps, waste collection routes, and quantity of waste collected. As early interactions with stakeholders showed their interest in correlating utility data with demographic and climate variables, we identified relevant databases from the Australian Bureau of Statistics (ABS) and the Bureau of Meteorology (BOM) to be incorporated into SID.

## B. Technical Architecture and Work Flows

Figure 2 gives an overview of SID's technical architecture and main workflows involved. SID receives data in diverse file types (e.g. Excel spreadsheets, plain text files, CSV files, ESRI shapefiles) and in heterogeneous structures (e.g. number and types of columns). We use the standard Extract, Transform and Load (ETL) process<sup>9</sup> to migrate these data into an optimized data warehouse environment.



**Figure 2. Technical architecture and workflows of SID**

The ability to conduct analysis at multiple spatial scales has been identified as an essential component of SID. ETL plays a crucial role in shaping data to give SID this ability. Currently, two geographic hierarchies are supported in SID. The first is based on the Australian Statistical Geography Standard (ASGS) released by ABS recently<sup>7</sup>. This hierarchy starts at Statistical Area Level 3 (SA3), and drills down to SA1 through SA2. The second geographic hierarchy is a two-step one where an LGA drills down to postcodes.

The data warehouse is based on a Star Schema design. Star Schema is a widely used data model for data warehousing in various real-world applications<sup>9</sup>. It organises data into one or more fact tables referencing any number of dimension tables. A star schema can simplify join queries and provide capability to analyse data from multiple dimensions, thus enabling a user to perform various drill down, roll up, slice and dice operations on data. In our data warehouse, each utility networks is modelled using a separate star schema. However, these network schemas and the schema for utility consumption are interconnected through common dimensions.

Geo-analytical tools (proprietary Geo-BI software *Yellowfin* in SID's case) are used to create interactive reports such as maps and charts, and interactive dashboards that assemble related reports. These reports are built on top of the optimized star schema-based data warehouse. End users access this interactive content via an online portal. The user interface is visually rich and

comprises of easy-to-use controls like filters that provide keys to intricate analysis while effectively concealing the complexity of calculations and database queries from the user. Visualization is a primary focus for the user interface as highly intuitive visuals play a pivotal role in successful policy support tools<sup>10</sup>.

### C. Applications

SID has a myriad of potential applications in the infrastructure domain that can provide planners and policy makers with ingredients needed to ensure a better service provision to communities. We briefly discuss two such applications next.

#### 1) *Relationships among Utility Usage, Socio-Demographics and Weather*

Figure 3 shows an analytical dashboard developed in SID that enables exploration of relationships among utility usage, demographic variables and weather parameters. This dashboard consists of three interactive reports. The map report starts at LGA level, and is drillable to postcode level. Moreover, the other two reports can be controlled by this map report. A user can select one out of several metrics, for example total residential electricity consumption, to be displayed on the map. The second report (radar chart) gives an overview of

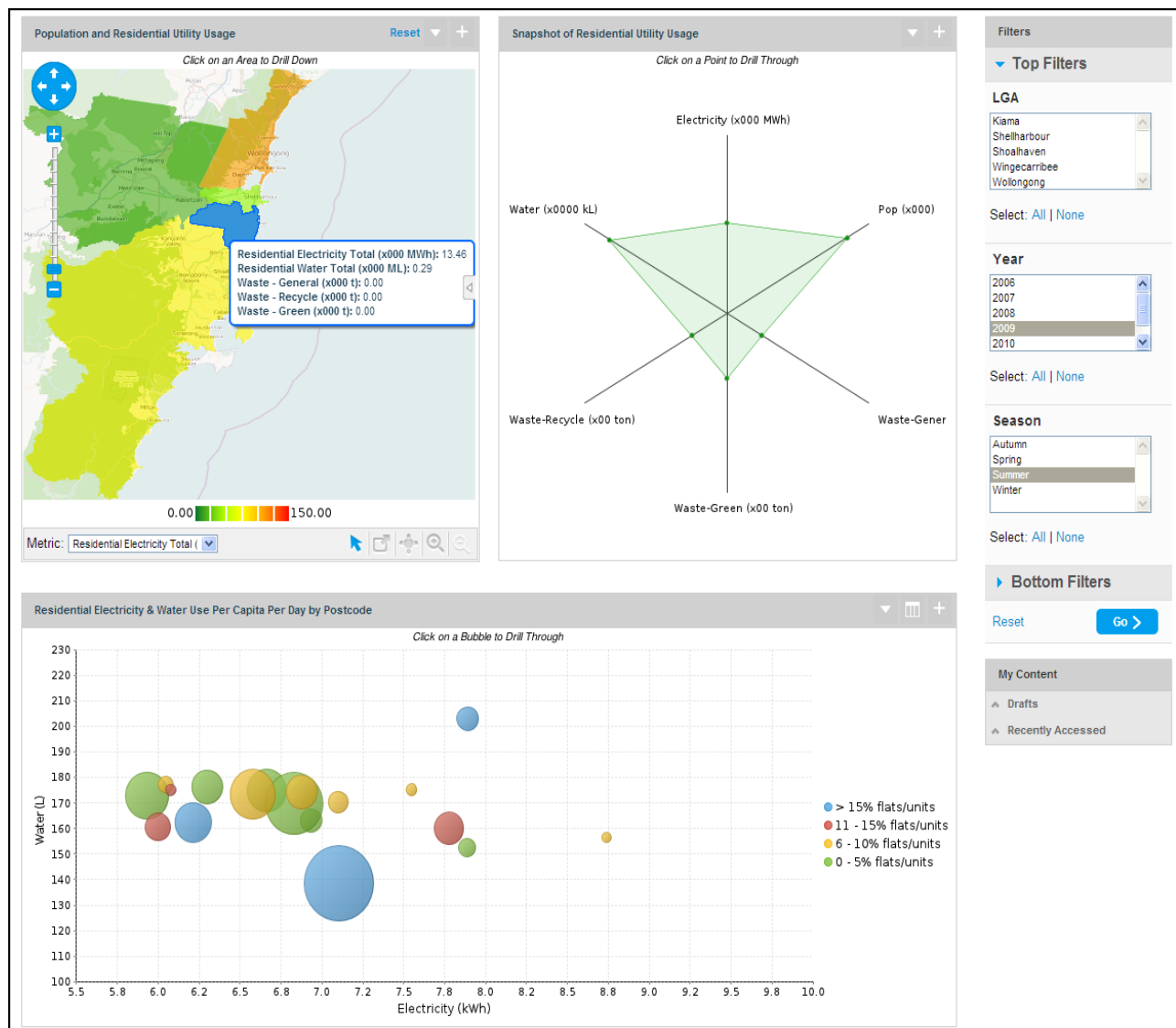


Figure 3. An interactive, geo-analytical dashboard used in SID



the utility usage for the active area on the map report. The statistical bubble chart shows the relationship between per capita water and electricity consumptions at postcode level. A bubble in this report represents a postcode, and the radius of a bubble is proportional to the population in that postcode while the colour of bubbles indicates the abundance of flats and units in a postcode. Filters to the right of the dashboard let users control all reports at once.

Multi scale spatial analysis is facilitated by the drillable map report, and the ability to update linked reports with the drill down or roll up on the map. Multi temporal analysis is enabled in this dashboard through a hierarchical filter. For the temporal analysis, two levels of disaggregation are possible: year and the seasons. Although SID facilitates further disaggregation in the time dimension through month, weeks, days up to minutes, this particular application limits this disaggregation to season level only. The main reason for this was the water consumption data for which the finest available temporal granule was season.

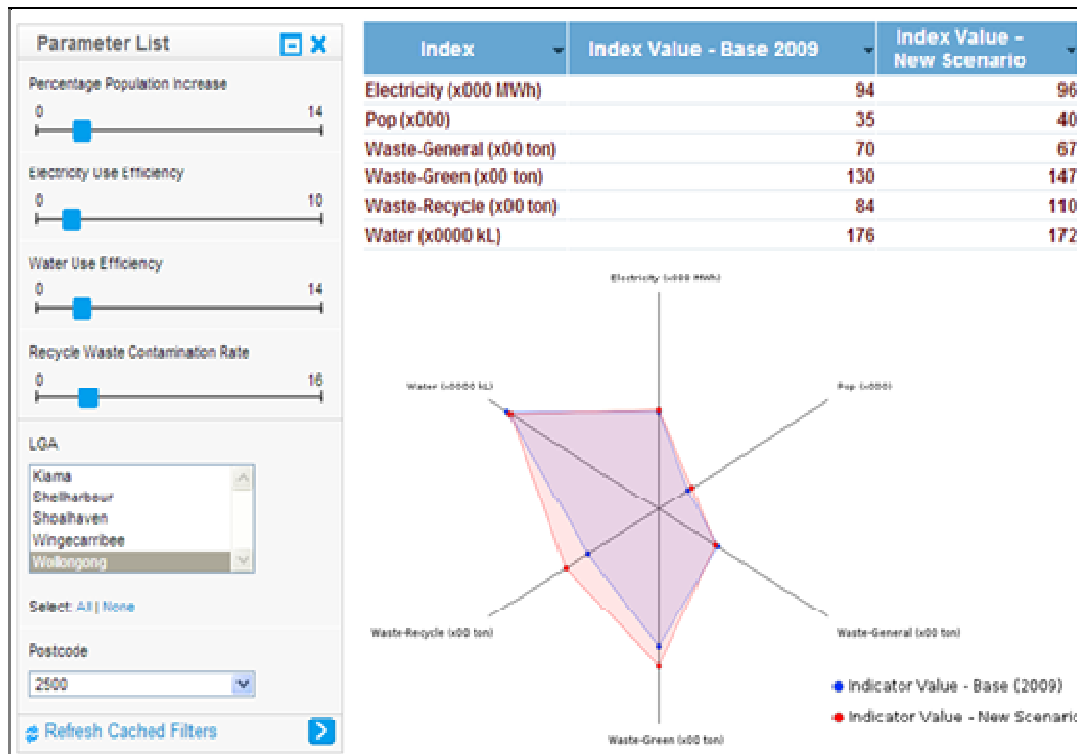
Perhaps, the most important feature of SID is its ability to cross spatial and temporal granules at will. For example, some patterns could be pertinent at postcode level only when viewed at seasonal intervals, while some other patterns may project well at LGA level at yearly intervals. SID has been designed to uncover such hidden patterns in data.

Statistical bubble chart in Figure 3 is an example for several ways by which SID uncovers interrelationships among various utilities and demographic variables at multiple temporal resolutions. While this chart enables the user to appreciate general trends, it is also an ideal tool to spot outliers.

#### **D. What-If Scenario**

What-If analysis is an indispensable tool by which planners could estimate the potential impact of changes in a set of independent variables on one or more dependent variables<sup>11</sup>. Traditionally, BI solutions have been designed to analyse past data only, and they lack the ability to provide any sort of anticipation of future trends.

Hence, what if analysis is a modern and cutting edge feature of BI that makes such tools sit on the top of the BI pyramid<sup>11</sup>. SID as a Geo-BI solution provides planners with ample opportunities to leverage historical data for better planning through what if analysis. Figure 4 shows one of several integrated reports in SID that let users to carry out what if analysis.



**Figure 4. What-if scenario analysis**

Using  
this  
integrated

report, a planner can estimate the expected utility use for a given LGA or postcode under various scenarios, and compare the predicted value with the base case (table and graph). While the planner predicts the utility usage in 5 years, for example using a certain value for the population increase, he could also see what efficiency gains would keep the expected usage within manageable limits. This report keeps complexity of the implemented calculations behind the scene, and presents the non-savvy user with a few easy-to-use sliders and filters to perform multiple scenario analyses on utility usage.

#### IV. Discussion and Conclusions

Despite the traditional use of Geospatial Business Intelligence (Geo-BI) as a tool to help increase profits within a single organization, we believe that it possesses a largely untapped potential that warrants its use as a generic decision support system in planning and policy domains. In this study, we demonstrate that the Geo-BI can be adopted to provide the much needed integrated view on infrastructure service at local and regional level.

Geospatial aspect is crucial in this solution to take the best out of majority of the infrastructure-related data that contain a location reference. Moreover, identifying patterns and associations among various infrastructure services and usage in space-time is crucial in decision making. Needless to mention that an interactive map is a better visual when it comes to communicating location-related information. BI provides tools and methods needed to tap into

diverse sets of disparate data and load them into an optimized data warehousing environment for efficient analysis and reporting. With the involvement of right people from the design phase to final usage phase, Geo-BI can be turned into a powerful tool for the governance of infrastructure services.

Using a case study for the Illawarra region of New South Wales, Australia, we demonstrated how tools and processes in Geo-BI could be harnessed to develop a user-friendly solution, which we termed the SMART Infrastructure Dashboard (SID), geared towards the governance of infrastructure services at the local and regional levels. Through a web-based portal, SID provides planners and policy makers a visually-rich interface to perform powerful spatio-temporal analyses needed to identify patterns and associations among multiple utility-related variables in space and time. Moreover, SID facilitates what if scenario analysis offering a way by which planners could anticipate and plan for future trends in utility usage. Future research will involve extending SID's capabilities to investigate the propagation of cascading failures in interconnected networks.

### Acknowledgement

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# Modelling Infrastructure Systems for Resilience and Sustainability

Sarah Dunn<sup>a\*</sup>

Sean Wilkinson<sup>a</sup>**Error! Bookmark not defined.**

Gaihua Fu<sup>a</sup>

Richard Dawson<sup>a</sup>

**Abstract:** Modern infrastructure systems are vital to the functioning of modern society. They promote social well-being, support economic development and are crucial in mitigating the effects of natural hazards. While there is some understanding of their mitigation role, there has been little quantifiable work on how they support our societies or how they stimulate economic development. Some recent analysis of infrastructure systems have shown that many of these seemingly different systems display similar architectures to each other leading to the hypothesis that the evolution of these systems is a result of underlying drivers that are common to all. This paper presents a network model that captures the growth of infrastructure networks in terms of architecture, hazard tolerance and geographical characteristics. The results presented in the paper suggest that the model may be the basis for an enhanced understanding of the role that infrastructure plays in sustaining our communities.

**Key words:** Complex networks; Graph theory; Infrastructure systems; Modelling; Resilience.

## I. Introduction

Infrastructure systems, such as water, transport, communication and energy networks form the backbone of our modern communities<sup>1</sup> and are crucial to the functioning of our modern society<sup>2</sup>. These systems not only promote social well-being and support economic productivity, but they also play a crucial role in mitigating the effects of natural hazards and as such are designed to have lower than usual probabilities of failure. However, it is not possible to engineer out all possibility of failure and therefore not only does failure occur, but when it does it can lead to great suffering in our communities. For example, in the aftermath of hurricane Katrina two dozen hospitals were left without electricity, meaning that they could not operate essential laboratory and x-ray equipment, dialysis machines and ventilators, resulting in many potentially preventable deaths<sup>3</sup>. The above argument demonstrates not only the need to ensure that these systems can provide at least a baseline level of service in the aftermath of a disaster, but also to

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<sup>a</sup> School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, UK.

\*Corresponding author: Sarah Dunn [sarah.dunn@ncl.ac.uk](mailto:sarah.dunn@ncl.ac.uk)  
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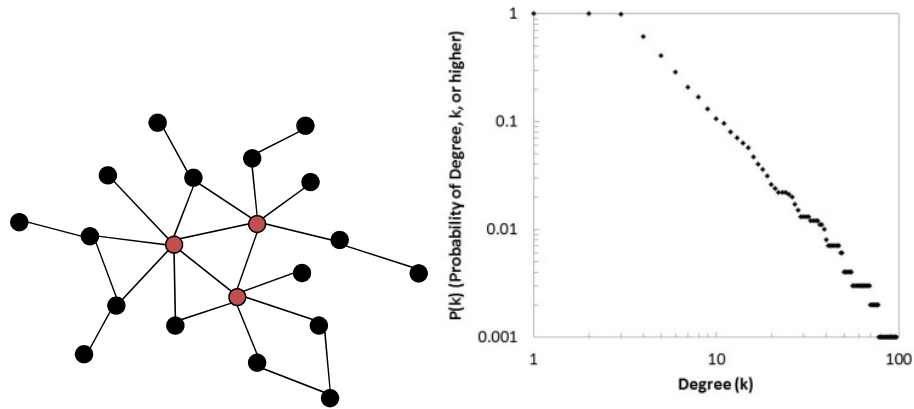
develop tools that can assess the behaviour of these systems subjected to very rare events and what this baseline should be.

The current design approach for our infrastructure systems is to design the individual components to have a particular probability of failure. However, this silo-based approach does not ensure adequate system performance in the overload situation (i.e. it does not guarantee that a baseline level of service will be delivered when these systems become damaged by the effects of a natural disaster). Systems are traditionally modelled using physically based models (e.g. a hydraulic model for a water distribution system), which are useful at providing scenario based information. However, due to their complexity, they can be found lacking when used to inform us of the resilience of the system and highlight structural inadequacies.

To solve this problem, recent studies have applied network graph theory to model the complex interactions between individual components. In this approach, only the topology of the system is considered which is modelled as a series of nodes and connecting links. Studies using this approach have discovered that infrastructure systems display surprising similar network architectures, which has led to the hypothesis that the evolution of these systems is a result of underlying drivers that are common to all. However, this approach can be deficient when used to model systems spread over wide geographic regions as it purely consider the connections between components and not the locations of the components themselves. In this paper, we present a network model which captures these underlying drivers governing connections between individual components, but extend this to capture the drivers governing the geographic growth of these systems.

## **II. Modelling Infrastructure Systems using Topological Complex Networks**

Infrastructure systems can be modelled using network graph theory by using nodes to represent the individual components (e.g. power stations, communities in an electrical distribution system for example) and links to model the connections between these individual components (e.g. the transmission lines). Previous studies analysing infrastructure systems have shown that many of these systems naturally configure to specific network architectures or network classes. These network classes describe different patterns of nodal connectivity (i.e. different arrangements of the nodes and links) and are characterised by a ‘degree distribution’. It is this distribution that allows for the distinction between different classes of network. The degree distribution of a network is the probability distribution of the degrees of all nodes in the network, where the degree of a node is equal to the number of links connected to it. Infrastructure systems have been shown to belong to one of two network classes: the scale-free or exponential network class<sup>4,5,6</sup>. Both of these classes are similar in that they comprise a small number of highly connected nodes and a larger number of poorly connected nodes. A sample scale-free network and a characteristic degree distribution are shown in Figure 15.



**Figure 15. Showing (a) a sample scale-free network and (b) the characteristic degree distribution of a scale-free network.**

The Internet and the World-Wide-Web were the first infrastructure systems to be classified as scale-free by Albert et al.<sup>4</sup>. In a further study they went on to consider the underlying drivers which governed the formation of connections between nodes in these networks and used this to develop a network generation algorithm capable of forming synthetic networks with the scale-free degree distribution<sup>7</sup>. This algorithm is based upon the ideas of *growth* and *preferential attachment*<sup>8</sup> and starts with an initial number of isolated nodes,  $m_0$ , which are usually a small percentage of the total number of nodes in the network. New nodes are then added to the network at each ‘time-step’ (incorporating the idea of *growth*) until the total number of nodes in the network is reached. These added nodes have between 1 and  $m_0$  links attached to them and connect to the existing nodes in the network based upon the idea of *preferential attachment*. As such, the probability of connecting to an existing node is based upon the degree, with nodes with a higher degree being more likely to ‘attract’ a link from the new node (i.e. the rich get richer). It is this rule of *preferential attachment* which results in the formation of a few highly connected nodes and many poorly connected nodes in the network (as seen in Figure 15).

Other infrastructure systems have been classified as exponential networks, the most notable of which are power grids<sup>5,9,10,11</sup>. In similar manner to scale-free networks, previous studies have also considered the drivers governing the formation of connections in this network class and have used this information to develop network generation algorithms. Wilkinson et al.<sup>12</sup> developed one such generation algorithm which was based upon the scale-free algorithm<sup>7</sup>, but with one notable difference. In their algorithm, Wilkinson et al.<sup>12</sup> also considered the geographical characteristics of the system, rather than focusing on topology alone. Many infrastructure systems which belong to the exponential network class are distributed over wide geographic areas, for example power grids can be distributed over whole countries or even continents. To reflect this in their algorithm, Wilkinson et al.<sup>12</sup> modified the idea of *preferential attachment* to incorporate a spatial component. They proposed that poorly connected nodes can capitalise on their close proximity to a highly connected node by attracting links that were bound for the high degree node, arguing that the probability of attachment is based upon both degree and proximity. They showed that this network generation algorithm is capable of generating proxy networks for real world infrastructure systems (using the European air traffic network as an example).

One of the main advantages of classifying infrastructure systems (other than identifying the underlying drivers) is that this information can be used to gain an insight into the inherent hazard tolerance of each system. For example, both scale-free and exponential networks have been shown to be resilient to a random hazard (e.g. failure due to random events, such as lack of maintenance), but vulnerable to targeted attack (e.g. a targeted terrorist attack). This is because a random hazard has a small chance of removing a highly connected node, whereas a targeted attack will often remove these important nodes seeking to cause the maximum disruption to the network<sup>13</sup>. It can be seen from Figure 15(a) that the removal of one of the three high degree nodes (red) will cause a larger impact to the network than the removal of one of the more numerous smaller degree nodes (black).

### **III. Development of Spatial Network Model**

Whilst, there has been a great deal of research considering the topological hazard tolerance of these networks, there has currently been very little research on the implications of the geographical distribution of an infrastructure system on its hazard tolerance. Traditional graph theory focuses on topological models where it is only the presence of a connection between two nodes which is considered to be important. The little work that has studied real world spatial networks focuses mainly on characterising the topology of the system (into one of the network classes), while the spatial element of the same network receives less attention - if not neglected entirely<sup>8</sup>. This spatial component may not seem important; however as shown in the development of the exponential generation algorithm and subsequent hazard tolerance analysis by Wilkinson et al.<sup>12</sup> it can not only have a significant influence on the layout of the network, but is crucial in defining its tolerance to real world hazards.

Traditional graph theory has discovered underlying drivers governing the formation of connections between pairs of nodes; we now expand upon this to consider the drivers determining the geographic location of nodes within a network. To achieve this we develop an algorithm to generate nodal layouts (with different characteristics) by simplifying the method of cellular automata. This technique has previously been used to predict urban growth around cities, including San Francisco<sup>14</sup> and Washington<sup>15</sup>. However, these models require the input of detailed historical data (including: historical maps, aerial photographs and digital maps) at regular time intervals from the initial settlement in the study area to the present day. This data is normally obtained from a variety of sources and there are often problems with assembling the dataset, including: inconsistent dimensions of features, generalisation in historical maps, different projections of the study area and different coordinate systems. As such the main disadvantage in this method is that the accuracy of the results is highly dependent on the quality and quantity of the historical data<sup>15</sup>, indeed if insufficient historical data for the study area is obtained then it is not possible to generate a synthetic model. Therefore, we propose a new method which incorporates and simplifies the ideas behind cellular automata to generate proxy nodal layouts for real world networks.

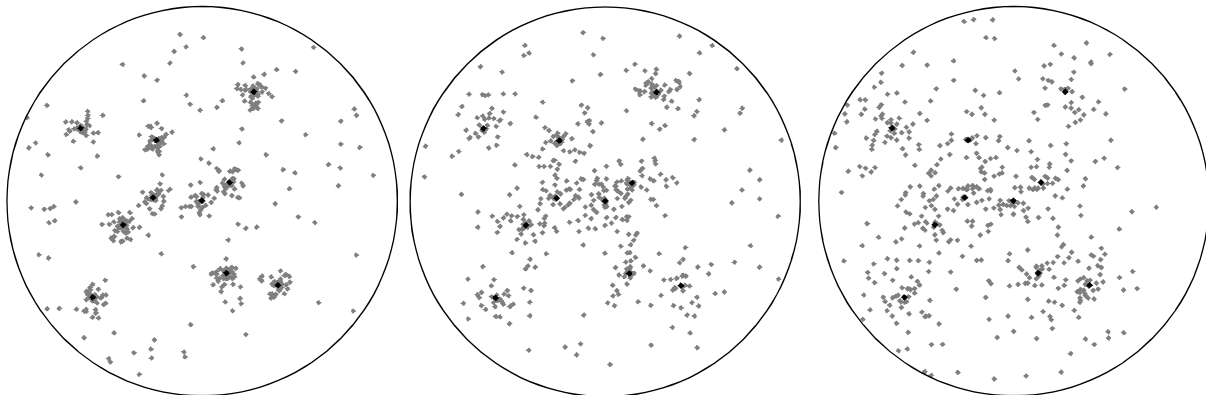
In a similar manner to cellular automata, the algorithm requires the input of a set of initial conditions, from which the nodal layout forms over a given timeframe. These initial conditions define the spatial boundary of the network (or the study area), the number of seed nodes and the location and initial radius of these seed nodes. Using these inputs the network is allowed to



‘grow’ and the remaining nodes are added individually to the network at each ‘time-step’ until the total number of nodes is reached.

At each time-step the algorithm determines if an added node will be located within the radius of one of the individual clusters or will be located outside the influence of all of the clusters, depending on a user specified probability value. By allowing a small proportion of the total number of nodes in the network to be located outside the cluster radii, a rural environment over the whole of the spatial boundary is represented. However, if the added node is to be located inside the radius of a cluster, then this node is ‘attracted’ to the different individual clusters based upon a calculated probability value. This probability value is dependent upon the density of the cluster and is calculated by dividing the number of nodes within the influence of the cluster by the cluster radius. This probability value encompasses the idea that a city, with a high population density, can be expected to have more nodes (representing train stations, for example) than a rural community which has a significantly lower population density. With the addition of a new node to the cluster, the radius of the cluster is allowed to expand outwards, in order to simulate the ‘growth’ of an urban area. This growth is logarithmic meaning that it increases rapidly for the first few nodes added to the cluster and then reduces to only increasing marginally with further added nodes.

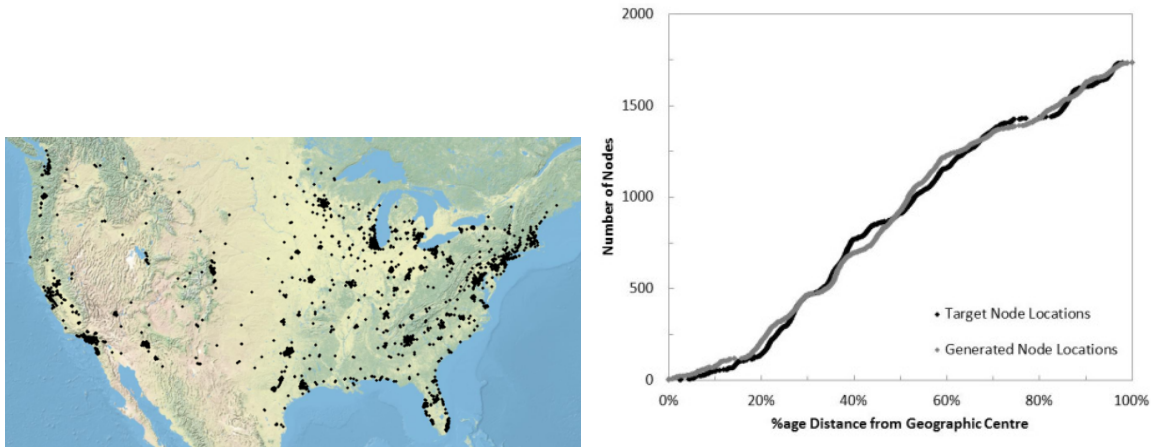
The algorithm also incorporates a variable to alter the density of the network as a whole; the visual effects of this variable (termed  $C_D$ ) can be seen in Figure 16. These three nodal layouts have been generated using the same seed locations and radius values, but different  $C_D$  values (100, 200 and 300 respectively).



**Figure 16. Three nodal layouts generated using the clustering algorithm with  $C_D$  values of (a) 100, (b) 200 and (c) 300. Where the black dots represent the seed nodes and the grey dots show the added nodes, the outer circle defines the spatial boundary of the network.**

To validate this clustering algorithm we use it to generate a real world nodal layout for the Target dataset (shown in Figure 17 and obtained from edigitalz.COM<sup>16</sup>). In a similar manner to Wilkinson et al.<sup>12</sup> we also determine the spatial distribution of stores (nodes) in this network (shown as the black dots in Figure 17(b)). The proxy nodal layout for this network was generated by visually defining the location of the seed nodes (as the centre of the high density areas on the GIS image, Figure 17(a)) and determining their radius values by considering the density of the cluster. This information was then inputted into the clustering algorithm and nodal layouts generated for different  $C_D$  values (to find the best fit for the real world data). The spatial

distribution for the proxy network has been shown as grey dots on the corresponding spatial distribution in Figure 17(b). It can be seen that this proxy nodal layout is in good agreement with the actual real world nodal layout, meaning that the model is capable of determining the underlying drivers governing the formation of real world nodal layouts. We can now use this information to assess the hazard tolerance of these spatial networks, as a geographic hazard will affect the nodes and links depending on their location.



**Figure 17.** Showing (a) the spatial layout of nodes in the Target dataset and (b) the spatial distributions, where the black dots correspond to the actual network and the grey dots to the generated nodal layout.

#### IV. Conclusion

This paper has presented a network model which captures the growth of infrastructure systems in terms of their network architecture, geographical characteristics and hazard tolerance. Previous studies have considered the underlying drivers which determine the architecture of the network, but have failed to consider the spatial distribution of the same network, which can have dramatic effects to the perceived hazard tolerance of the network. Therefore, this paper developed a network model which also considers the underlying drivers governing the location of individual components within an infrastructure system. The results presented in the paper suggest that these models may form the basis for an enhanced understanding of the role that infrastructure plays in sustaining our communities and also in stimulating economic development.

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# **An Evaluation of Spatial Network Modeling To Aid Sanitation Planning In Informal Settlements Using Crowd-Sourced Data**

Tomas Holderness<sup>a\*</sup>  
Ruth Kennedy-Walker<sup>b</sup>  
David Alderson<sup>c</sup>  
Barbara Evans<sup>b</sup>

**Abstract:** Limited water and sanitation infrastructure in rapidly urbanising informal settlements can present significant health and environmental risks to the populations of developing nations. Where formal piped networks are not available, road-based sewage treatment-transportation options have been cited as a viable alternative. However, little research has been undertaken to evaluate the long-term operational costs of such systems. In this paper we present an evaluation of network modelling, as a novel method to evaluate the costs of road-based sewage treatment-transport options. Such analysis is made possible using crowd-sourced, open geospatial data sets that allow us to examine costs based on different spatio-topological network configurations. It is envisaged that engineers could use such a tool as part of the sanitation planning process, to evaluate sanitation network implementation options. This study provides an evaluation of the methods using a case study from the Kibera settlement in Kenya.

**Key words:** Sanitation; Infrastructure; Spatial Analysis; Networks.

## **I. Introduction**

In many developing nations a lack of sanitation infrastructure results in significant risks to public health through unsafe collection and treatment of sewage before discharge<sup>1,2</sup>. This is often exacerbated in rapidly urbanising and informal settlements, which have limited access to formal water and sanitation services<sup>3</sup>. For example, Banerjee and Morella state that only half of Africa's large cities have sewerage networks<sup>4</sup>. Where formal piped networks are not available, the only option for collection and transportation of waste is via the road network, a process that is often

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, New South Wales, 2500, Australia

<sup>b</sup> School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, United Kingdom

<sup>c</sup> School of Civil Engineering, University of Leeds, Leeds, West Yorkshire, LS2 9JT, United Kingdom

\*Corresponding author: Tomas Holderness tomas@uow.edu.au

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undertaken manually<sup>5</sup>, as infrastructure constraints of informal settlements mean that motorised collection and emptying vehicles are often unable to access toilet facilities<sup>5</sup>.

In response to this, the United Nations HABITAT programme has developed the 'Vacutug', a small motorised vacuum pump truck specifically designed to meet the infrastructure challenges of developing nations<sup>6</sup>. However, a major barrier to the successful implementation of road-based sanitation schemes is the operational and maintenance costs associated with sewage transportation vehicles<sup>6,7</sup>. This is especially the case with Vacutugs due to their limited capacity (0.5 m<sup>3</sup>) and speed (5 Km/h)<sup>6</sup>. A potential solution to decrease costs is to employ an intermediate transfer station for waste, located at the boundary of a settlement, where Vacutugs deposit waste and from which large tanker trucks can collect and transport sewage the remaining distance to a treatment plant over the main road network<sup>5,6</sup>.

With respect to these issues we propose that when planning a road-based sewage sanitation scheme, spatial network analysis be used to optimise the location of transfer stations, in order to minimise associated costs of sewage transportation. However, whilst in developed nations network analysis can be performed within a Geographical Information System (GIS) using formal spatial data (e.g. topographic survey), in developing nations the utility of such techniques is restricted by the limited availability of spatial data. One solution is to use crowd-sourced maps which provide an alternative to nonexistent or incomplete formal spatial data sources<sup>8-10</sup>. Created by volunteers using GPS data, aerial photos and existing paper maps, crowd-sourced maps have been successfully developed in a number of developing nations and used for community engagement<sup>9</sup>, urban planning<sup>11</sup>, and disaster response<sup>12</sup>. Crucially, the information provided by these maps is playing an increasingly important role in the lives and livelihoods of many inhabitants of developing urban regions worldwide<sup>13</sup>. In these regions, crowd-sourced spatial data-sources have been cited as being more current, complete, and reliable than traditional formal sources of data<sup>9,12</sup>. The Map Kibera project is an example of one such scheme where members of a developing urban community, working with OpenStreetMap (OSM), for the first time created a free and open, highly-detailed map of the informal settlement of Kibera (Nairobi, Kenya). The data collected includes land cover, the road/footpath network, and the location of amenities such as water taps, toilets, and health clinics<sup>13,9,11</sup>.

As such, crowd-sourced spatial data present a viable alternative to traditional formal data-sources, with which to perform road network analysis in developing urban regions. This study presents an evaluation of the utility of spatial network modelling for improved sanitation using crowd-sourced spatial data. A simple model representing a road-based sewage treatment-transportation system which could be implemented to manage waste from Kibera's public toilets was created<sup>5,6</sup> and used to identify the optimum location and number of transfer stations around Kibera to minimise sewage transportation time across the network.

## II. Methods

Kibera is an informal settlement located 5 Km south west of the centre of Nairobi, Kenya, and spans an area of more than 550 acres<sup>9</sup>. Sanitation provision for Kibera's 200,000 residents is poor, with little or no formal sewage infrastructure<sup>14</sup>. Where they exist, toilet facilities are shared and data from the Map Kibera project show 158 public toilets within the Kibera boundary. For the purpose of this study we use a hypothetical road-based improved sanitation scheme using a

Vacutug and transfer station system to manage waste from Kibera's public toilets<sup>5,6</sup>. The Dandora treatment plant was selected as a potential end-point for treatment of Kibera's sewage. Dandora is Nairobi's largest treatment plant and is situated approximately 20 Km east of the city centre<sup>15</sup>. Dandora is a lagoon-based plant with a daily treatment capacity of 80,000 m<sup>3</sup>, which is discharged as partially treated effluent to the Nairobi river system<sup>15</sup>.

Road, footpath, and land cover data were extracted from OSM data for Nairobi and Kibera. The Kibera boundary and locations of public toilets were obtained from the Map Kibera project<sup>9</sup>, and spatial database tables representing each of the extracted data sets were created. A number of pre-processing steps were undertaken before creation of the road network model for analysis. First a Boolean multicriteria evaluation was used to identify areas suitable for transfer stations at the Kibera-Nairobi boundary. Based on descriptions of existing transfer stations from the literature<sup>5,6,14</sup>, suitable land areas were selected if; they were free of existing development, had an area greater than 64 m<sup>2</sup>, were within 50 metres of the Kibera boundary and were within 5 metres of a road connected to both Kibera and Nairobi. This ensured that the Vacutug journey distances were minimised and that there was suitable access for both Vacutugs into Kibera and large tanker trucks to Nairobi. The centroids of areas identified as suitable for transfer stations were used to represent transfer station nodes in the network model.

The second pre-processing step was to calculate travel time for each road in the network so that shortest path calculations of routes could account for both distance and vehicle speed<sup>16</sup>. The lengths of each road were based on their geometric length as derived from the OSM data. For all roads inside Kibera road speeds were set to 5 Km/h based on maximum Vacutug velocity<sup>5</sup>. Road speeds in Nairobi were set to 25 Km/h based on averages recorded during an empirical study for the International Vehicle Emissions Model<sup>17</sup>. The time to travel each road segment was then calculated using road length and speed.

After pre-processing a spatio-topological model of the sanitation road network was constructed using the spatial database schema and coupled Python interface to the NetworkX graph analysis package, developed by Newcastle University<sup>18</sup>. The complete road network model for Kibera and Nairobi consisted of 19,558 edges covering 4,686,483 Km of road, and 16,347 nodes representing road junctions, toilets, the transfer stations, and the treatment plant.

To minimise transport time and so minimise sewage transportation costs, the network model was used to identify the transfer station which represented the total minimum time required for sewage transportation. Total sewage transportation time was defined as the time taken to transport one Vacutug load of sewage from each toilet in Kibera to a transfer station and then the transportation by large tanker of the accumulated waste from transfer station to the Dandora treatment plant. To achieve this, the sum of the journey time over the shortest paths from each of the toilets in Kibera to a transfer station, plus the travel time from transfer station to treatment plant was computed. The shortest path between network locations was calculated using Dijkstra's algorithm and the transfer station with minimum total time was identified as the most efficient (Equation 1).

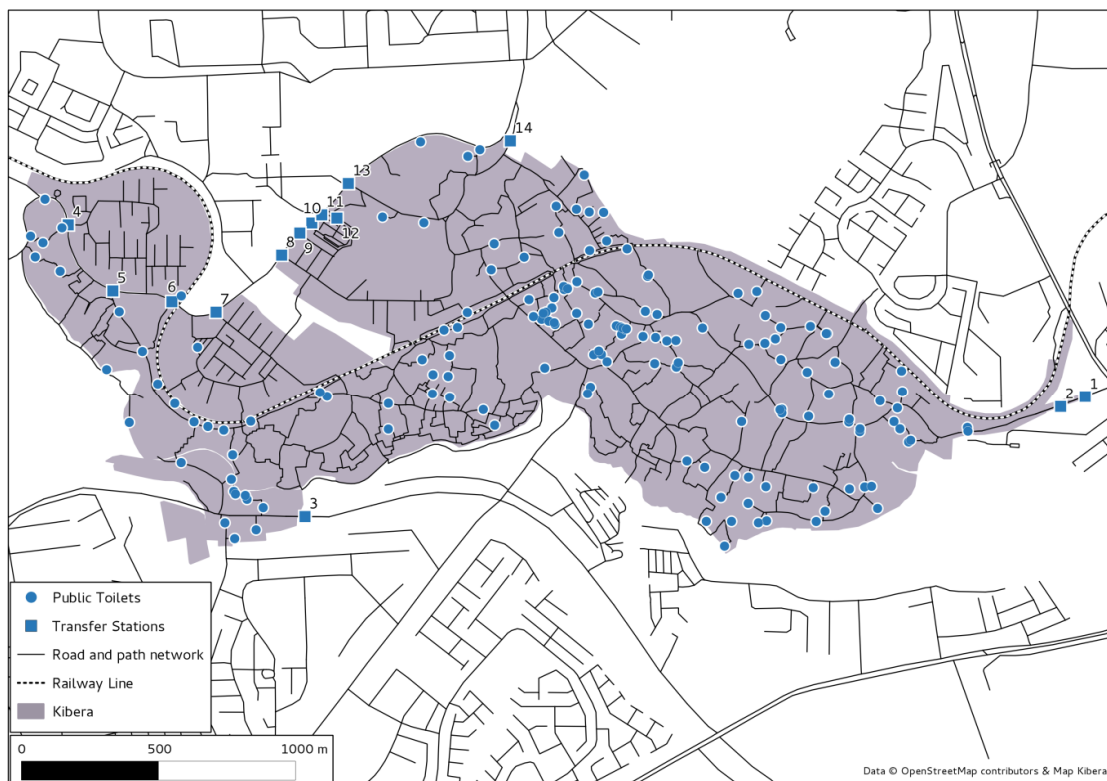
$$t_j = \min \left( \left( \sum_{i=1}^n d_{ij} \right) + d_{jk} i_n \frac{c_{lt}}{c_{vt}} \forall_j \right)$$

**Equation 1. Calculating the station with the minimum total sewage transportation time.**

In the transportation time calculation the number of large tanker journeys from transfer station to treatment plant was proportional to the capacity ratio between Vacutugs and large tankers. Given a Vacutug capacity (cvt) of 500 litres and a large tanker capacity (clt) of 10,000 litres<sup>5</sup> it can be seen that for every 20 Vacutug deposits at the transfer station the large tanker must make one journey to the treatment plant. Therefore, the total number of large tanker journeys is this ratio multiplied the number of toilets (Equation 1). Thus, total sewage transport time via each transfer station is the time taken for a Vacutug journey from each of the 158 toilets in Kibera (i) and the 7.9 large tanker trips required from the transfer station (j) to the treatment plant (k).

### III. Results

Figure 1 shows the locations of 14 areas of land identified as suitable for transfer stations by the MCE. The spatial distribution of stations around Kibera is uneven, with 11 of the 14 stations lying to the northwest. Two stations lie to the far east of the settlement (one and two) and are closest by straight-line distance to the Dandora treatment plant (~25 Km). One additional station (station three) is situated to the southwest of Kibera. Stations four, five, and six present interesting locations selected by the MCE as they are situated on a road which bisects two segments of Kibera and unlike the other stations are situated amongst a number of toilets in north-western Kibera, reducing the distances to nearby toilets at these sites.



**Figure 1. Map showing Kibera settlement, public toilets and locations identified as suitable for transfer stations by the multicriteria evaluation.**

Table 1 shows the total sewage transport time for each station from which it can be seen that the total sewage transportation time from station three is 42.39 hours, the minimum value for all stations (Equation 1). Station three represents the location that provides the best balance between overall distance to the treatment plant and total distance for all 158 Vacutug journeys. The total sewage transportation time from station three is 5.51 hours less than that of station 14, the next fastest route, and 13.34 hours less than station four, the least efficient station which is situated at the western end of the settlement. These results are to be expected somewhat as the geography of Kibera shows that the settlement runs broadly east west (Figure 1). This means that station four is not only furthest from the Dandora treatment plant but also from the majority of Kibera's toilets, increasing both its Vacutug and large tanker journey times. In contrast, stations three and 14 (the first and second most efficient station locations) are located more towards the centre of Kibera thus reducing the time for Vacutug journeys to toilets across the settlement from these stations.

However, whilst station three exhibits the lowest overall sewage transport time, the journey time from transfer station to treatment plant (large tanker journey time) is between 1.61 and 0.04 hours slower than the large tanker trip times from the next six fastest transfer stations (Table 1). Additionally, the standard deviation of Vacutug journeys across all stations in Table 1 ( $\sigma = 3.03$ ,  $\bar{x} = 40.97$  hours) is almost eight times that of the large tanker journeys ( $\sigma = 0.39$ ,  $\bar{x} = 9.92$  hours). As a result the Vacutug journey times have a greater influence on overall station transport time than large tanker journeys. The latter have a low variation due to the lack of ring roads in Nairobi which forces many vehicles traversing the city to pass through the central business district<sup>19</sup>, leading to convergence of shortest path route from each transfer station to the treatment works, minimising differences in large tanker journey times.

**Table 1. Sewage transport times for each transfer station, based on the first model configuration.**

Transfer station	$\Sigma$ Vacutug time (hours)	Large tanker time (hours)	Total sewage transport time (hours)	Number of large tanker journeys
<b>3</b>	<b>32.32</b>	<b>10.07</b>	<b>42.39</b>	<b>7.9</b>
14	37.99	9.91	47.90	7.9
13	39.73	9.92	49.64	7.9
11	40.21	9.97	50.18	7.9
10	40.43	9.99	50.41	7.9
9	40.56	10.00	50.56	7.9
8	40.79	10.03	50.82	7.9
7	41.55	10.13	51.69	7.9
12	41.69	10.04	51.73	7.9
1	43.09	8.96	52.05	7.9
6	42.34	10.19	52.52	7.9
2	43.97	9.08	53.05	7.9
5	43.53	10.26	53.79	7.9
4	45.37	10.36	55.73	7.9



#### IV. Conclusions

This study has demonstrated the use of network modelling to calculate sewage transportation time over a road-based sanitation network, cited as a solution to poor sewage infrastructure in developing nations<sup>6</sup>. This research was enabled by using crowd-sourced geospatial data, which provided information on the road network and existing sanitation infrastructure within Kibera not previously available<sup>9</sup>. Using the network model it was possible to identify the transfer station location with the minimum sewage transportation time that could be used to reduce costs in a road-based improved sanitation scheme<sup>6</sup>.

As populations in informal settlements around the world continue to rise<sup>3</sup> it will become increasingly necessary to evaluate the long term operating costs of improved sanitation options, to provide an economically sustainable method of reducing health and environmental risks. As such, future feasibility studies will need to consider transportation network options for sewage alongside conventional piped networks and in particular, the associated current and future costs of different systems. There is currently limited research about road-based faecal sludge emptying and transportation, and methods to assess its effectiveness<sup>7</sup>. It is envisaged that the network modelling tools and methods presented in this paper will help to improve the knowledge gap related to transport based sanitation services and could be used by engineers as part of the sanitation planning process to optimise the configuration of improved sanitation networks in developing nations.

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### List of notation

- $t_j$  is the minimum sewage travel time for station  $j$  where station  $j$  has the lowest time of any station, using the single station model configuration
- $t_m$  is the total minimum sewage travel time using the multiple station model configuration
- $j$  is the transfer station node
- $i$  is the public toilet node
- $k$  is the treatment plant node
- $d_{ij}$  is the shortest path between toilet node  $i$  and transfer station  $j$  weighted by time
- $d_{jk}$  is the shortest path between transfer station  $j$  and treatment plant  $k$  weighted by time
- $i_n$  is the number of toilets serviced by transfer station  $j$
- $c_{vt}$  is the Vacutug capacity
- $c_{lt}$  is the large tanker capacity



# A Semi-Deterministic Approach for Modelling of Urban Travel Demand

Nam Huynh<sup>a\*</sup>  
Nagesh Shukla<sup>a</sup>  
Albert Munoz<sup>b</sup>  
Vu Lam Cao<sup>a</sup>  
Pascal Perez<sup>a</sup>

**Abstract:** This paper presents a methodology to construct travel related activity schedules for individuals in a synthetic population. The resulting list of activity schedules are designed as an input into a micro-simulator for urban transport dynamics analysis. The methodology involves two main steps. The first step generates a synthetic population based on census data sourced from the Australian Bureau of Statistics (ABS). The second step assigns individuals in the synthetic population activity schedules using Household Travel Survey (HTS) data related to the geographical area of interest (in this case, the Sydney Greater Metropolitan area). Each individual is assigned an ordered set of trips, travel purpose, travel mode, departure time and estimated trip time. The significance of the methodology is twofold in that it generates a synthetic population aligned with area demographics, as well as generating activity schedules that realistically represent how the population uses existing transport infrastructure. The methodology also preserves the inter-dependencies (in terms of the sequence, travel times and purpose of trips) of individual's daily trips, in contrast to many trip generators for transport micro-simulation purposes. A case study of Randwick area in southern Sydney is presented where the proposed methodology is applied. Case study data is validated against real world results and the scalability and applicability to other urban areas are discussed.

**Key words:** Travel diary; Synthetic population; Agent based modelling; Travel demand; Household travel survey data

## I. Introduction

Of critical importance to efficient urban transport planning is an understanding of the interdependencies between populations and transport infrastructure. The daily activities of populations, where they go, using what transport infrastructure and why is a topic typically addressed through static, aggregate models to represent complex urban dynamics. These models are tasked with informing the policies that influence much of the transport infrastructure

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, NSW 2522, Australia.

<sup>b</sup> School of Management and Marketing, University of Wollongong, NSW 2522, Australia

\*Corresponding author: Nam Huynh [nhuynh@uow.edu.au](mailto:nhuynh@uow.edu.au)

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investments of an area. As such, these models need to incorporate the detailed interactions a heterogeneous population would have with existing or proposed transport infrastructure. In many cases, the models employed lack the depth to enlighten some of the hidden feedbacks transport policy may have on urban transport networks. A critical component for models of urban transport is the construction of individual-level activity schedules (travel diary) that, when aggregated, realistically represent population travel demand. Such activity schedules should comprise the sequence of trips each individual in the population makes as well as trip attributes such as travel mode, trip purpose, and departure time.

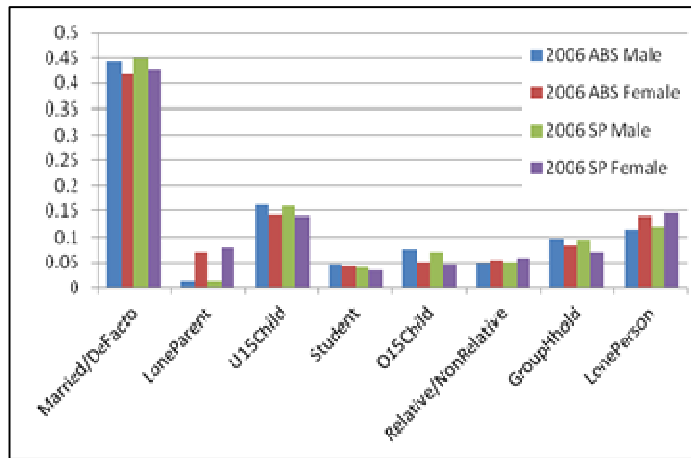
State-of-the-art models in travel demand modelling can be classified as trip based; tour based; and activity based. In trip based approach, each individual trips is modelled as independent and isolated trips *i.e.* no connections between the different trips. In the tour-based approach, trips start and end from the same location (home, work, etc) and are modelled as independent tours. As such, tour based approach lacks temporal granularity, and ignore inter-relations among independent tours. Over the past two decades, researchers have largely adopted activity based modelling to overcome these drawbacks, by deriving travel demand from the activities that individuals need or wish to perform<sup>1-4</sup>. Activity-based approaches offer the advantage of incorporating spatial, temporal, transportation and interpersonal interdependencies (in a household) to model activity/travel behaviour. Furthermore, this approach reflects scheduling of activities in time and space and has been adopted in various operational land use and transport simulation models such as *ALBATROSS*<sup>4</sup>, *TRANSIMS*<sup>5-6</sup>, *AMOS*<sup>2</sup>, *PCATS*<sup>1</sup>.

The emerging field of activity-based models for travel demand modelling has received much attention in the literature<sup>4,7-10</sup>. However, the majority of the activity based modelling methods presented are based on utility maximisation models<sup>11</sup>, Markov models<sup>12-13</sup> and rule based models<sup>1,2,4,14</sup>. In utility maximisation models, a set of integrated tours form the basis for individual activity and travel demand modelling. For each tour, the choices of destination, mode and time of day are modelled as nested logit models with random utility maximisation objective functions<sup>11</sup>. Others have employed Markov models (with activities as state) to estimate the daily, activity patterns, encompassing the interdependency of sequential activity types, timing and duration<sup>12</sup>. On the other hand, rule based models execute the process of decision-making by using heuristic rules<sup>15,4</sup>.

Approaches to date have used sets of decision making algorithms, such as determining activity patterns, travel time of day, activity durations, travel mode choice, etc. for assigning travel details to individuals in a synthetic population. Each decision making step is modelled based on statistical models (e.g. nested logit, Markov) or decision trees (e.g. classification and regression trees), which has an associated error term. As a result, the overall error rate of an activity list assignment is compounded as the output of a particular decision making step is the input to the next. Furthermore, these approaches consider individual level travel details assignment, ignoring the interdependencies that exist among individuals in a household. With a view to address these limitations, a single-step approach using household level semi-deterministic search method is proposed in this paper. The purpose is to assign travel diary to each individual in a synthetic population.

## II. Synthetic population (SP) construction

There are two major approaches to generating synthetic populations, synthetic reconstruction and the combinatorial optimisation (CO). For in-depth reviews of each approach, interested readers are referred to the work of Huang and Williamson<sup>16</sup>, Ryan et al.<sup>17</sup>, Muller and Axhausen<sup>18</sup>, and Kurban et al.<sup>19</sup>. One issue that remains unaddressed in population synthesis is the incorporation of household resident relationships. Such a synthetic population would have to simultaneously synthesise the correlations between individuals and households against the real population in order to facilitate the collective decision making critical to agent based models. The value in these models lies in their ability to captures realistic behaviours of individuals in their interactions with infrastructure systems, and the subsequent value to urban policy design. For example, a household with a single parent with two children under 15 years old would have a considerably different transport need and behaviours than a married couple household with no kids.

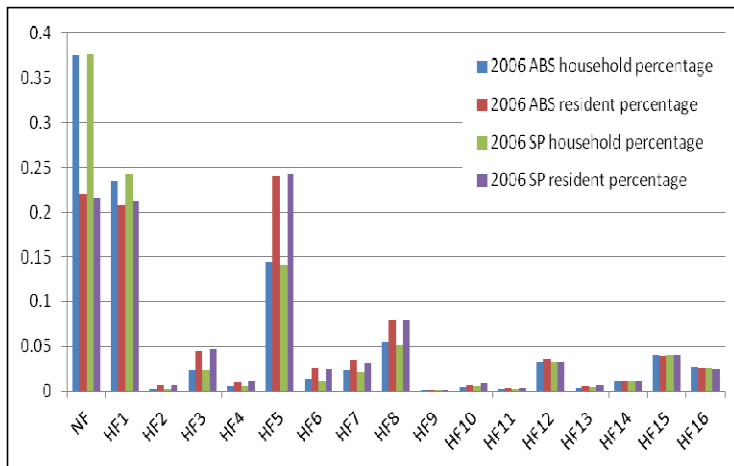


**Figure 1. Percentage of males and females by household relationship of Randwick area in 2006.**

In this study, a synthetic population is generated for agent based modelling purposes using a variation of the CO approach<sup>20</sup>. Individuals are selected from an individual pool and allocated into households in a household pool to satisfy the distribution of household compositions in the study area. Each record in the individual pool represents an individual of the synthetic population and has four attributes, age, gender, household relationship and income. In contrast to the CO approach, the pool of individuals is instantiated from an aggregate data set representing the demographics distribution of the study area rather than extracted from an existent disaggregate survey data. The pool of households is instantiated from a different aggregate data set. Each record in this pool represents a household and has three attributes, number of males and number of females of the residents, and household type.

Using this algorithm, a synthetic population was constructed for Randwick area in Sydney using the 2006 ABS census data. In 2006, the area had approximately 106000 individuals living

in around 47000 households. Visitors were not included in the synthetic population as they were not permanent residents of the study area. Figure 1 compares the proportion of household relationships of male and female individuals in the synthetic population of Randwick area against the original ABS data. Figure 2 compares the 17 household types in the synthetic population by number of households and number of residents against the original ABS data. Household types HF1 to HF16 are family households, distinguished by the number of parents (i.e. 'Married'/'DeFacto' individuals) and the number of children types (i.e. 'U15Child', 'Student', 'O15Child'). Group household members and lone persons live only in households of type NF (non-family households). The correlations between these values validate that the methodology as one that can construct a realistic synthetic population for agent based modelling purposes that matches well with key statistics of the real population in the study area.



**Figure 2. Percentage of 2006 household types in Randwick area.**

### III. Travel Diary Assignment to Synthetic Population

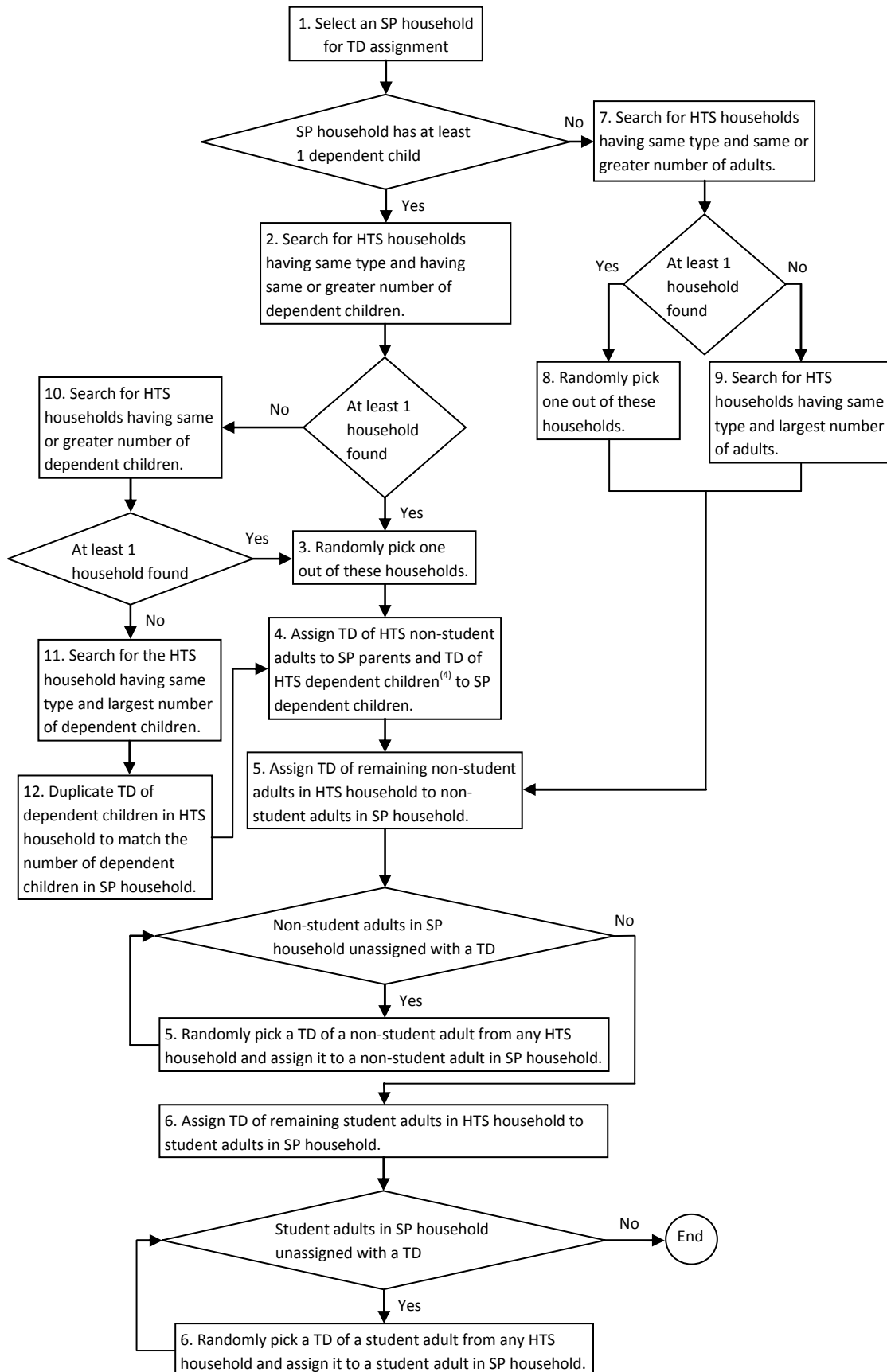
The household travel survey (HTS) data is the largest and most comprehensive source of information on individual travel patterns for the Sydney Greater Metropolitan Area (GMA). The data is collected through face to face interviews with approximately 3000-3500 households each year (out of 5000 households in the Sydney GMA randomly invited to participate in the survey). Details recorded include (but are not limited to) departure time, travel time, travel mode, purpose, origin and destination, of each of the trips that each person in a household makes over 24 hours on a representative day of the year. Socio-demographic attributes of households and individuals are also collected. The total number of trips included in the HTS data used in this paper is approximately 161000.

HTS data was used in this study to assign travel diary to individuals in each household in the synthetic population constructed. The method proposed for activity schedule assignment comprises two steps. The first deterministically searches in HTS data for households that best match the household type, the number of children under 15 years old, and the number of adults of a synthetic population household. This stage is described in steps 2, 7, 9, 10, and 11 in Figure 3. The deterministic search carried out in those steps gradually relaxes the constraints on exact matching of the number of children younger than 15 years old so that the search always returns at least one HTS household. The second step randomly selects a HTS household from the list of households identified in stage 1 and assigns travel diary to individuals in the HTS household to

those in the synthetic household. The random selection follows a uniform distribution, see steps 3, 4, 5, 6, 8, and 12 in Figure 3.

At the conclusion of this process, each individual in the synthetic population has an activity schedule with a sequence of trips for a typical week day, as well as purpose, mode, departure time, and estimated trip time of each trip, totalling 509000 trips made in the synthetic population of Randwick area. Because the sampling process

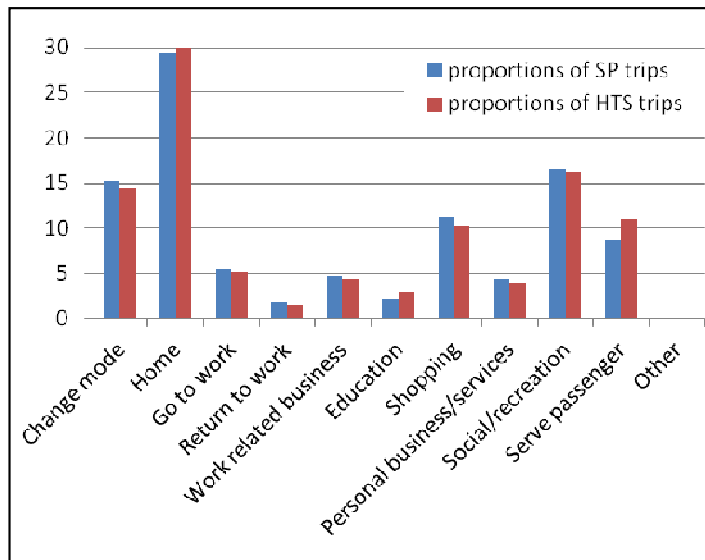




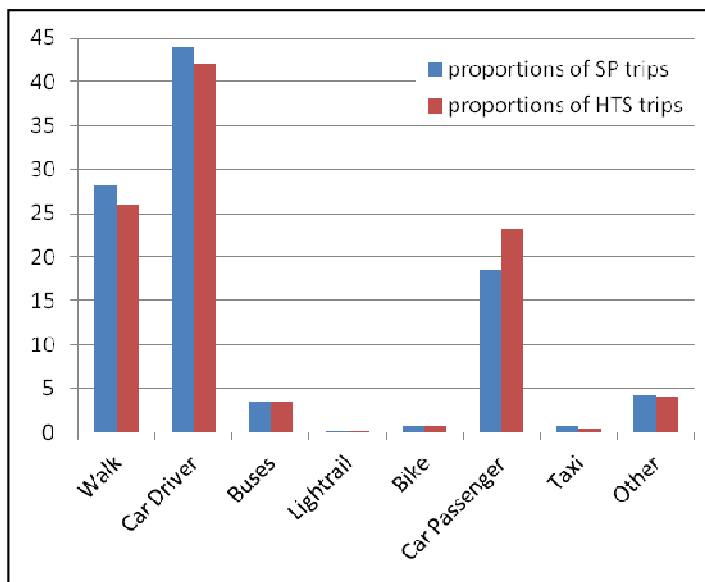
**Figure 3. Operational design to assign travel diary from HTS data to synthetic population**

from HTS data was carried out at household level, the inter-dependencies among individuals in a synthetic population household are preserved.

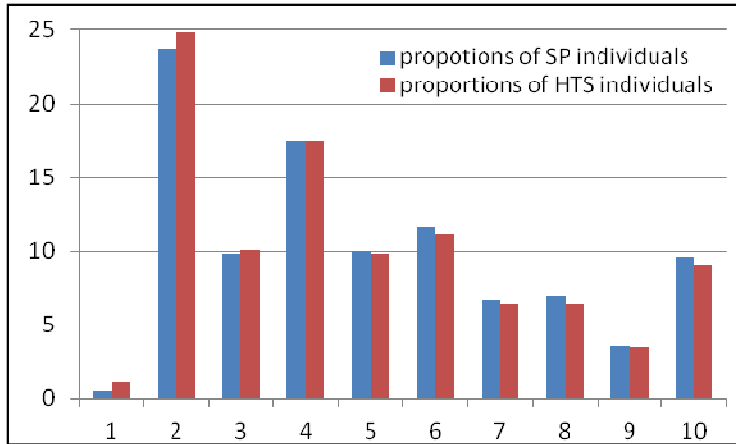
Activity schedules needs to realistically represent the patterns of travel demand of that area in order to be deemed suitable for input into traffic models. While no survey data is available to specifically detail the travel demand of Randwick area, Randwick synthetic population activity schedules were validated against HTS data of the whole Sydney GMA. Figure 4 compares the trip count proportions by trip purpose in synthetic population travel diary with HTS data. Figure 5 compares the proportion of trips counts by trip modes. Figure 6 compares the percentage of individuals in the synthetic population against that in HTS data by the number of trips made daily.



**Figure 4. Proportion of trip counts by purposes**



**Figure 5. Proportion of trip counts by modes**



**Figure 6. Percentage of individuals by number of trips made**

These validations affirmed that the activity schedules generated using the semi-deterministic sampling method presented accurately mimic travel demand, satisfactorily reproduces the distribution of trip counts by purpose as well as the distribution of individuals by the number of trips made a day. The methodology also indicates that driving, walk and car passenger are the three dominant travel modes, consistent with HTS data. There are some deviations, which are attributed to various factors, such as the mismatches of distribution of household types and/or household compositions (i.e. type of individuals living in a household) in the synthetic population and in HTS data. For example, a lower proportion of children under 15 years of age exist in the synthetic population compared to that in the HTS data. This discrepancy would result in a lower proportion of car passengers.

#### IV. Conclusions

This paper proposed a generic methodology to generate a realistic activity schedules for a synthetic population. The methodology was applied to construct a synthetic population for Randwick urban area in Sydney and assign activity schedules to each individual in the population. Comparisons of key statistics of the synthetic population against 2006 ABS census data validate the suitability of the algorithm presented in constructing a realistic synthetic population for simulation modelling purposes. Validation against the HTS data for the whole Sydney GMA confirmed that the constructed activity schedules successfully reproduce the travel demand patterns in the Randwick urban area. More importantly, it preserves the inter-dependencies (in terms of the sequence, travel times and purpose) of daily trips of individuals in a synthetic population household, which many trip generators for transport micro-simulation purposes ignore.

The activity schedule of an individual as constructed by the methodology details the sequence of trips that individual makes in a day, as well as trip attributes such as travel mode, trip purpose,

departure time and estimated trip time. Given specific locations for each of the trips, they provide complete inputs into a transport micro-simulator (e.g. Transims). The execution of such a micro-simulator provides a bird's eye view of traffic dynamics on a road network as well as actual travel times. This information is not only essential to assisting urban planning but a valuable input into an agent based model to simulate mode choice of the population. Such a simulation model facilitates a more realistic prediction of future travel demands in the study area.

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# A Study of the Dynamic Behaviour of Daily Load Curve for Short Term Predictions

K.A.D. Deshani<sup>a\*</sup>  
Liwan Liyanage – Hansen<sup>b</sup>  
M.D.T. Attygalle<sup>a</sup>  
A. Karunaratne<sup>a</sup>

**Abstract:** Electricity demand is one of the most controversial topics in Sri Lanka as the price of electricity increases rapidly, due to the scarcity of electricity generation sources to meet the demand. Fulfilling the peak demand, starting around 6.30p.m and ending around 9.30p.m, of the load curve is identified as the most crucial aspect that needs to be addressed. During this period, high cost power plants are used to generate electricity, which cannot be met using other low cost options such as hydro power. The Ceylon Electricity Board has to bear a huge loss in order to accommodate this high demand at peak times. Therefore, it is an essential task for a developing country as Sri Lanka to consider developing strategically approached mechanisms to provide a reliable electricity supply at an affordable price. This research focuses on studying the statistical nature of the daily load curve for different consumer categories and for different days of the week to capture the dynamics of electricity usage. An extensive literature is carried out to identify similar research and methodologies used to arrive at a solution by dynamically predicting the daily load curve and smoothing the peak using Demand Side Management strategies.

**Key words:** Short Term Load Forecasting; Demand Side Management

## I. Introduction

Electricity demand has become one of the most controversial topics in Sri Lanka as the price of electricity increases rapidly, due to the scarcity of electricity generation sources to meet the demand. Electricity demand varies in accordance with consumers' activities with respect to time of the day and the day of the week. As a result of these variations, the total daily load requirement is never a constant throughout a particular day. Thus predicting electricity demand accurately is considered as one of the most important aspects to optimize the electricity production, transmission, distribution and even to plan for fulfilling future electricity demand. These predictions can be mainly classified into three categories as short term, medium term and long term forecasts where each type has special advantages in decision making regarding the electricity industry. This study is mainly focused on short term load

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<sup>a</sup> Department of Statistics, University of Colombo, Colombo 03, Sri Lanka

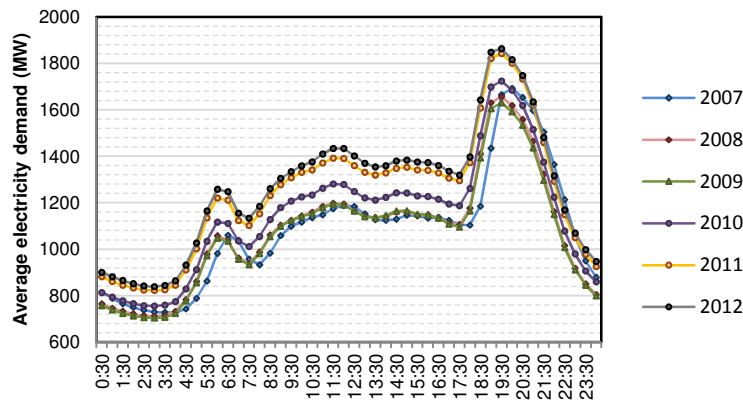
<sup>b</sup> School of Computing and Mathematics, University of Western Sydney, Australia

\*Corresponding author: Kariyawasan Deshani [deshani@stat.cmb.ac.lk](mailto:deshani@stat.cmb.ac.lk)

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forecasting which can be used to manage available daily electricity generation sources in an optimal manner.

Daily electricity load curve which can be drawn to represent the electricity load as a function of time, plays an important role in short term load forecasting. When considering the average daily load curve in Sri Lanka, a clear pattern can be observed over the past years with a gradual increase of load from year to year (Figure 1). It is noticeable that there are two sudden increments in the morning and in the night of each plot. The peak demand, starting around 6.30p.m and ending around 9.30p.m is identified as the most crucial aspect that needs to be addressed. During this period, high cost power plants are used. Therefore, the Ceylon Electricity Board has to bear a huge loss in order to accommodate to this high demand at peak times. It is an essential task for a country to consider developing strategically approached mechanisms. As at the early stage of this research, an extensive literature survey carried out to identify similar projects and methodologies used in related issues will be presented in this paper.



**Figure 1: Change in daily load curve over the years.**

## II. Predicting the Electricity Demand

In order to curtail the sharp peak in the load curve, as the initial step, future electricity demand should be predicted accordingly. This forecast should be a short term one as the demand varies from minute to minute with respect to various reasons and efficient decisions should be taken where necessary. Literature reveals the importance of short term load forecast for the control and scheduling of power systems, as the predicted values will be taken as inputs for the scheduling algorithms<sup>1</sup>.

### XV. Incorporating Additional Factors

Predominantly forecasts are based on a mathematical combination of previous values. In short term load forecasting, special attention should be paid to increase the accuracy as even a small deviation may result in a huge loss. Since electricity demand is influenced by factors like meteorological conditions, seasonal effects, special events, customer class, population and economic factors, some researchers had incorporated appropriate factors to improve the accuracy of the short term load predictions. Moreover, researchers are now trying to incorporate operators' experience and heuristic rules when they develop expert systems.

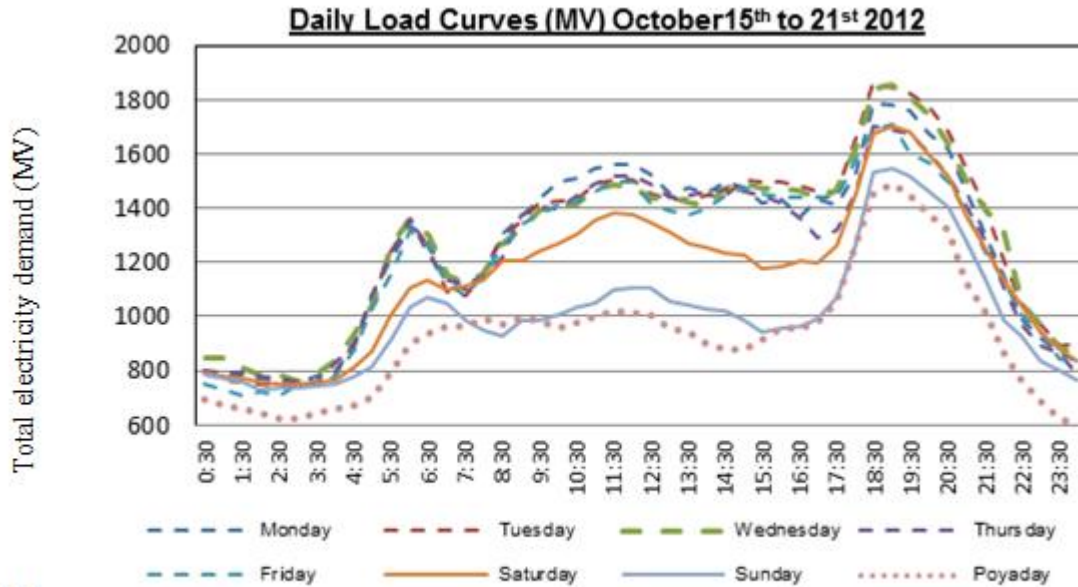
When considering meteorological conditions, temperature has been used by many of the researches in different ways; average daily temperature<sup>2</sup>, weekly average temperature and weekly<sup>3</sup>. Rather than selecting a single value for the temperature reading, some authors had considered temperature inputs of several cities in tropical, moderate, cold and hot areas to represent the varied weather conditions<sup>4</sup>. Some have also used cloud coverage<sup>5</sup> and wind speed<sup>6</sup>. Rahman and Hazim had tried to incorporate the weather-load relationship to design a weather sensitive model for the load forecast<sup>6</sup>. They had considered 12 weather related parameters which had not been considered for other studies. To smooth out temperature fluctuations and to account for the temperature load lag a new variable had been incorporated.

Soared and Medeiros had incorporated the effects of different types of days to the model as holiday, working day after and before holiday, Saturday after a holiday, working only during the mornings, working only during the afternoons, Special holiday and the seven days of the week<sup>7</sup>. Borges, Penya and Fernandez also had used similar type days and weekends<sup>5</sup> while Cho et al.<sup>3</sup> also had used day types and bank holidays. They also had performed a principal component analysis according to the day type and a segmentation scheme based on the first principal direction.

For the short term load forecast of the Taiwan power system, a research has embedded the facility to update the fitted model by allowing operators to use their heuristic rules to modify the forecast<sup>8</sup>.

For this research, apart from the collected half hourly daily electricity load data, from 2007 to 2012 the dataset was augmented by adding new variables. Considering the literature, different day types, daily rainfall and temperature readings of 21 stations have been identified as crucial variables. When considering the descriptive analysis, a clear difference in the load curve can be observed with respect to the type of day (Figure 2). A clear shift can be seen for weekdays and weekends as the displayed in the randomly selected week in Figure 2. In addition, as an economic factor, Gross Domestic Product will also be used after checking its significance to the model.





### III.

**Figure 2: Different patterns of load curves in weekends and weekdays.**

### XVI. Techniques Used in the Literature

The literature regarding short term load forecasting reveals that, a huge variety of researches exists in different fields (especially in the field of engineering). Forecasting methods range from conventional time series models to more sophisticated artificial intelligent approaches. Alfares and Nazeeruddin have classified the techniques used for electricity load forecasting to nine categories as models based on multiple regression, exponential smoothing, iterative reweighted least-squares, adaptive load forecasting, stochastic time series, ARMAX models based on genetic algorithms, fuzzy logic, neural networks and expert systems<sup>9</sup>.

The final objective of this research is to implement a real-time computer system which updates the model with the inclusion of new data. For this purpose, a technique combining statistical methods with artificial intelligence approaches is to be utilized. Therefore literature regarding contemporary short term load forecasting methods and expert systems will be discussed.

Two-Level Seasonal Autoregressive model proposed by Soares and Medeiros consist a separate model for each hour of the day<sup>7</sup>. Each model has been constructed with a purely deterministic component related to trend and seasonality and special day's effect and a stochastic component following a linear autoregressive model.

Many researchers point out the importance of using intelligent techniques in the instances where quick weather changes leading to fail accurate predictions or nonlinear relationships<sup>4,10,11</sup>. Thus it seems appropriate in using neural networks and fuzzy logic systems in short term load forecasts. Senjyu et al. has proposed a one-hour-ahead load forecasting method using neural network with the correction of similar day data in order to reduce the neural network structure and learning time<sup>11</sup>. Euclidian norm with weighted factor has been used to evaluate the similar

days and the neural network is composed of three feed forward layers, consisting 9 input units, 20 hidden units and a single output unit.

Even though short term electricity forecast using neural networks is gaining more attention, there is a possibility of excessive data training, which usually increases the out-of-sample forecasting errors<sup>2</sup>. Hence they have proposed a new approach based on machine learning technique using support vector machines. To avoid the said weaknesses, an ensemble model of a promising novel learning technology called extreme learning machine for high-quality short term load forecasting of Australian National Electricity Market was developed<sup>12</sup>.

Recently hybrid approaches have become dominant in this regard. Cho et al. had proposed the first level of forecasting by modeling the overall trend and seasonality by fitting a generalized additive model to the weekly averages of the load and the second level by modeling the dependence structure across consecutive daily loads via curve linear regression<sup>3</sup>. At the first level, trends from weekly average loads had been extracted using a generalized additive model, where temperature and other meteorological factors are included as additional explanatory variables.

When there are unusual changes in the electricity load or other used external variables like weather conditions or any other uncertainty, fuzzy logic will often lead to an efficient approach. Fuzzy logic based systems also had performed well in dynamic environments<sup>10</sup>. Seetha and Saravanan have adopted a novel approach using a fuzzy back propagation algorithm to predict 24 hours load ahead<sup>10</sup>. Barzamini et al. has done a modification to the multi layer feedforward neural network by developing a fuzzy system known as Modifier in order to successfully handle abrupt changes in weather conditions and special holidays<sup>4</sup>. A fuzzy system that has been developed to incorporate experienced operator's heuristic rules has been proposed<sup>8</sup>.

Considering the gathered literature, a fuzzy inference system based on a back propagated neural network is to be developed for this research. As Seetha and Saravanan suggested, classification or clustering techniques will be used to find similar patterns to that of the testing pattern will be used in order to reduce the error<sup>10</sup>.

After predicting the 24 hours ahead load curve, it would be easier to schedule and manage available electricity generation options in order to take effective decisions easily by utilizing the available resources.

### **III. CURTAILING THE PEAK DEMAND**

Since electricity can be stored for future use by bearing huge extra costs, the power stations must produce electricity as and when required. In Sri Lanka, the required electricity is produced according to a merit order scheme that mainly considers the cost of production. Even though there are many types of generating options, only a few options can be used to cater to the peak time as certain generating options has to be continuously used throughout the day to get its optimum benefit of reducing the cost.

During the peak time, high cost diesel-fired thermal power plants should be used, as the demand during this particular time period cannot be met using other low cost options. In this case the CEB has to bare a huge loss, as production cost for one unit is much higher than the selling price of one unit to the customers. Considering the number of such units for which this extra cost has to be borne by the Government, it is an essential task for a country to consider developing a strategically approached mechanism to deal with this problem.

#### **XVII. Demand Side Management or Demand Response?**

Activities and incentive programmes implemented and administrated by utilities to modify energy consumption and load shape of customers can be considered as demand side management techniques. These include load control, load shifting, energy efficiency and conservation. Demand response can be seen as demand side management on the customer's terms, where the customer decides on what loads to control and for how long, often in response to an economic/price signals or special requests by utility<sup>13</sup>. Rahman and Rinaldy bring out that demand side management techniques provide workable solution for electricity industry as uncertainty in future demand, fuel prices, construction cost, availability and cost of power from other utilities and the regulatory environment<sup>14</sup>.

#### **XVIII. Techniques Used in the Literature**

Most of the demand response techniques can be fruitfully utilized when customers' have smart meters which monitor electricity loads with respect to time. Smart meters or Advanced Metering Infrastructure allow bi-directional, real-time communication between the utility and the consumer<sup>15</sup>. According to Rahman and Rinaldy demand side management activity can be characterized as a two level process; load shape objective and end use by technology alternatives or market implementation methods. These methods can be used in order to handle situations with steep peaks<sup>14</sup>.

Strbac, Farmer and Cory had tried out to redistribute the load rather than load reduction<sup>16</sup>. This method has to be applied bearing additional costs as load reduction periods are followed by load recovery periods and those increments are to be supplied by system generators. They had used combined linear programming in order to optimize the schedule of allocating the generators along with the optimal times and levels of load reductions.

The method proposed by Eissa tries to change the electricity usage of end-use customers from their normal consumption patterns in response to changes of electricity price over time or by giving incentive payments to lower the electricity usage at times of high wholesale market prices or when system reliability is jeopardized<sup>17</sup>. She has considered medium voltage industrial and commercial data and had tried to encourage reduction in peak demand by implementing time of use rates or intensive based programs. Based on different consumption patterns of customers' one of the above methods have been applied. A block scheduling model of load management for price-based demand response is suggested by Li, Jayaweera, Lavrova and Jordan under two different real-time pricing schemes: linear pricing scheme and threshold pricing scheme<sup>18</sup>. For linear pricing, the problem is formulated as a convex optimization problem and the optimal demand response profile is given as a two-dimensional water-filling solution. The suggested methodology consisting a dynamic pricing scheme that encourages the customers to adaption

optimal demand-response profile that will naturally lead to peak-load shaving and load profile flattening.

#### IV. Conclusion

Based on the literature, in order to make an accurate real-time short term electricity load prediction, a model based on artificial intelligence and appropriate statistical techniques can be used. Incorporating fuzzy logic will enhance the capabilities of the model to tolerate unusual, sudden changes to the considered aspects. Additional factors like weather conditions and different day's effect can be used to enhance the accuracy of the model. The predicted load curve can be taken as the input of the demand response technique. Most common methods among literature in order to shave the peak demand are based on a time of use pricing scheme or an incentive based load shifting method.

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# A General Framework for Infrastructure System Reliability Modelling and Analysis

Payam Mokhtarian<sup>ab\*</sup>  
Mohammad-Reza Namazi-Rad<sup>b</sup>  
Tin Kin Ho<sup>b</sup>

**Abstract:** An infrastructure system is inherently complex, with layers of both defined and subtle interfaces with other infrastructure systems and human users. High availability is desired, which implies stringent requirements on reliability and safety. Reliability analysis typically starts at component or sub-system level and aggregates through the system functional hierarchy. Because of the system complexity, incorporating occurrences of all possible interactions and scenarios is not always practical and failure data is often limited. Moreover, there are unobserved events among the sub-systems distributing either randomly or with temporal trend. To facilitate reliability analysis amid the complex environment and uncertain data, this paper proposes a general framework on modelling and aggregating reliability for complex systems with distinctive statistical approaches. The underlying principles will be illustrated and the suitability of the proposed techniques with respect to the data available will be discussed. This study contributes to the assurance of life-long productivity of infrastructure systems.

**Key words:** Infrastructure System; Reliability; Statistical Modelling.

## I. Introduction

The term reliability is used generally to express a certain degree of assurance that a component or a system will operate successfully or at least at a desired level in a specified condition during a certain period of time<sup>1</sup>. If a component fails, this does not necessarily imply that it is unreliable or consequently it makes the system unreliable or unstable. Main concerns are how frequently failures at the component level occur in a specified time period and how much the overall reliability of a certain system is affected by the failures at the component level. Generally, reliability of a component depends on three functions: i) *technical reliability* of a component refers to nature of the component and this reliability is assumed to be a constant value, ii) *mission reliability* depends on mission type and is not a constant value, and iii) *operational reliability* refers to the persons or operational systems that operate with the component<sup>2</sup>. There are some other reliability functions that can affect the total reliability of a

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<sup>a</sup> National Institute for Applied Statistics Research Australia, University of Wollongong, NSW 2522, Australia

<sup>b</sup> SMART Infrastructure Facility, University of Wollongong, NSW 2522, Australia.

\*Corresponding author: Payam Mokhtarian  
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component while the abovementioned functions are the most effective ones. To express the total reliability of a component, a number of statistical methods have been proposed<sup>1</sup>. These methods are mostly based on probabilistic behaviour of the component failure obtained experimentally.

The proposed statistical methods (derived based on the distribution of the failures) provide information on the performance of the components. It is only sensible to use this information to decide the reliability of the system. If data are available on the performance of components, it is possible to calculate or estimate the reliability for overall system. However, it is necessary to use a reliable method to calculate or estimate the reliability of the system constructed from these components. Firstly, the structure of this system must be defined in terms of its components. This is attained by the structure function with the associated concepts of paths and cuts.<sup>1,3,4</sup> If the components operate independently and have identical probabilistic mechanisms, the reliability calculation for the system is simplified. A simple and important combination of the reliability structure function is a linear combination in which the overall system reliability is the average of the components reliability. However, it is not practical to assume such a reliability structure function and non-identical components need to be considered, as well. To deal with this structure, a number of weighted and model-based methods have been proposed<sup>5</sup>.

Considering the definition presented for both component and system, it is easier to illustrate the system structure by a one-fold nested structure in which the system is the core and components are sub-systems. Moreover, the failure term is transferred to the performance in infrastructure reliability study. Generally, all infrastructures have this hierarchy and an infrastructure and its components are assumed to be system and sub-systems, respectively. In practice, it is important to obtain the total reliability of an infrastructure in term of performance. In real world, there are a number of infrastructures operating simultaneously or sequentially as their interdependency and sequential productivity should meet the requirement of a desired service. This definition is a natural extension of the hierarchical structure of a system. Hence, the structure of a set of infrastructure is expressed by a two-fold nested structure in which all infrastructures including their components are built on a main platform. In this paper, a general framework of reliability study for such hierarchical structure from the statistical perspective is presented.

The remainder of this paper is structured as follows. In Section 2, the structure function of reliability at the infrastructure level is studied. Section 3 describes the extension on the reliability structure function at the overall infrastructures level. Finally, Section 4 concludes the paper with a summary of proposed idea and a discussion of avenues for future researches.

## II. Infrastructure Structure Functions

Within an infrastructure consisting of  $n$  components,  $x_i$  denotes the state of the  $i^{th}$  component where  $x_i = 1$  if the component is operating and  $x_i = 0$  otherwise. The state of the infrastructure is determined by the structure function  $s(\mathbf{x})$  where  $\mathbf{x} = (x_1, x_2, \dots, x_n)$  is the vector of component states. The vector  $\mathbf{x}$  is a path when  $s(\mathbf{x}) = 1$  and is a cut when  $s(\mathbf{x}) = 0$ . The number of components in operation is

$$T(\mathbf{x}) = \sum_{i=1}^n x_i. \quad (1)$$

The number of paths of size  $k$  is denoted by  $P_k$  and hence the number of cuts of size  $k$  is  $C_k^n - P_k$ . An infrastructure structure based on the formation and operation of its components is categorised. A series infrastructure is an infrastructure in which all components must operate for an infrastructure to run and has productivity. The structure function is as follows

$$s(\mathbf{x}) = \prod_{i=1}^n x_i. \quad (2)$$

In this case there is only one path,  $x_1, x_2, \dots, x_n$ , which has size  $n$  and it is the minimal path. Within a parallel infrastructure structure, only one component needs to operate for the infrastructure to run and has productivity.  $s(\mathbf{x})$  is defined as follows

$$s(\mathbf{x}) = 1 - \prod_{i=1}^n (1 - x_i). \quad (3)$$

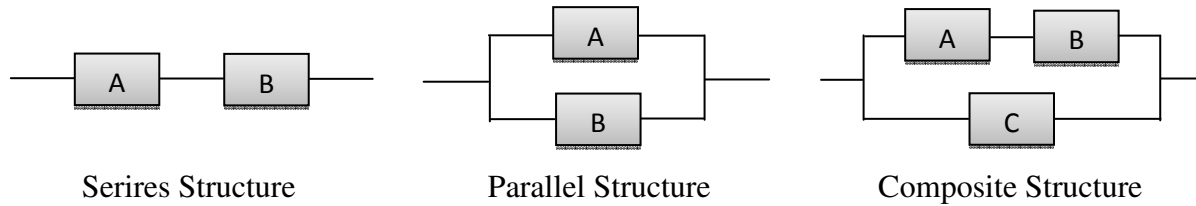
Here, every state equal to 1 is a path. Therefore, there are  $2^n - 1$  paths. This is a simple case of parallel infrastructure in which only one component is operating. With increasing the number of operating components in a parallel infrastructure, the total reliability will increase. The extension of a 1-parallel infrastructure is a  $k$ -out-of- $n$  infrastructure in which at least  $k$  components must operate for the infrastructure to operate.

Within a composite infrastructure structure, components are both in series and parallel form. In this type of infrastructure structure, the operating parallel section denoted by  $\mathbf{z} = (z_1, z_2, \dots, z_m)$ . As a result,

$$s(\mathbf{x}) = 1 - \prod_{i=1}^{n-m} (1 - y_i); \mathbf{y} = (y_1, y_2, \dots, y_{n-m}), \quad (4)$$

where  $\mathbf{y} = \mathbf{x} - \mathbf{z}$  and  $s(\mathbf{z}) = \prod_{j=1}^m z_j$ .

Figure 1 demonstrates three possible infrastructure structures discussed in term of components formation and operation where A, B and C are possible infrastructure components.



**Figure 1. Infrastructure structure respect to the components formation a simple infrastructure.**

Reliability of each component respect to set  $L$  can be defined by a probabilistic function as below,

$$R(L) = \Pr (\text{Component operates in set } L), \quad (5)$$

where set  $L$  is the level of satisfactory. In the context of failure analysis, this set is the life-time or the time that component works under a certain condition. The reliability analysis of the



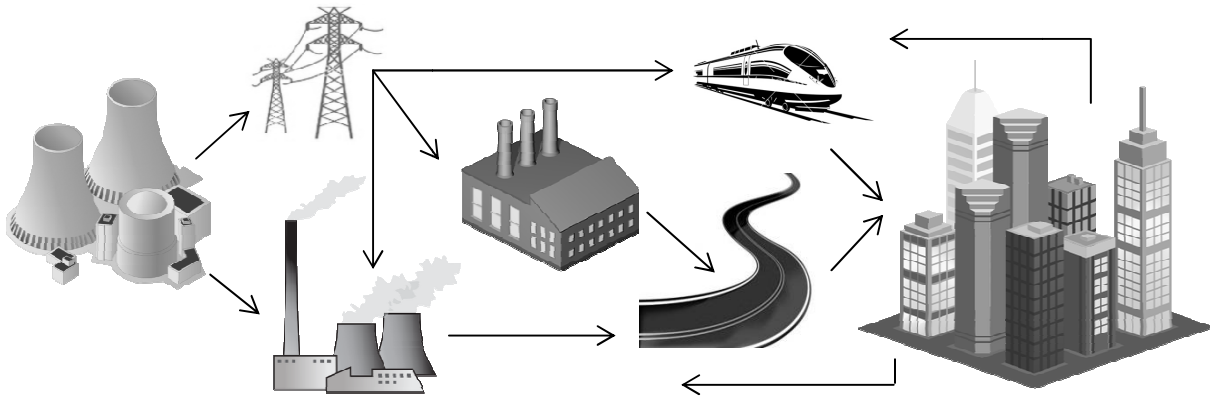
infrastructure structures presented in Figure 1 depends on the properties of system components. The reliability function of an infrastructure is defined by its structure function considering influence of its components on the system performance. For an infrastructure consisting of  $n$  components,  $\mathbf{w}$  is the weight vector and  $\mathbf{r}$  is a measurement for the effects of the reliability measured for  $i$  component on total reliability of this infrastructure, for which  $R_i$ . Here,  $R$  denotes the whole infrastructure and the overall reliability of this infrastructure is

(6)

where  $\mathbf{w} \cdot \mathbf{r}$  is inner product of weights vector and components vector.

### III. Infrastructure Reliability Models

This section investigates the total reliability of a set of infrastructures that operate simultaneously or sequentially. This can be expressed by a natural extension of the one-fold nested structure of an infrastructure to a two-fold nested structure. In order to study infrastructures while  $n$  is the number of components potentially operate within infrastructure a one-fold nested structure is considered for each of the  $n$  infrastructures. When a one-fold nested structure is considered for these  $n$  infrastructures on a main platform a two-fold nested structure is designed. Figure 2 illustrates the two-fold nested structure and interaction between the infrastructures as an example in which the assumed infrastructures operate in a main platform. Moreover, each infrastructure includes a number of components.



**Figure 2. An example of the two-fold nested structure and interaction between the infrastructures.**

Here,  $R$  is the total reliability of the  $n$  infrastructure while the infrastructure is the  $i$  component at the main platform. In case these  $n$  infrastructures are operating in series, the overall reliability is calculated using a linear weighted function as follows

$$R_K(\mathbf{X}) = \prod_{k=1}^K \omega_k R_k(\phi_k(\mathbf{x}_k)), \quad (7)$$

where  $\omega_k$  is the series effective weight of the  $k^{th}$  infrastructure. In case the infrastructures are operating in parallel, the overall reliability has a cumulative linear weighted function form as below

$$R_K(\mathbf{X}) = \sum_{k=1}^K \gamma_k R_k(\phi_k(\mathbf{x}_k)), \quad (8)$$

where  $\gamma_k$  is the parallel effective weight of the  $k^{th}$  infrastructure. The overall reliability for the composite structure of infrastructures in the main platform can be calculated. In this case, the infrastructures with series operation must be considered as one infrastructure with corresponding total reliability denoted by  $R_{S_1}(\mathbf{X})$ ,  $s_1 = 1, \dots, S_1$ . Consequently, all sets of series infrastructures should be considered as one infrastructure. In this study,  $G$  denotes the total sets of series infrastructures while the rest operate in parallel. Thus, the overall reliability of the  $K$  infrastructures has a cumulative linear weighted function form as follows:

$$R_Q(\mathbf{X}) = \sum_{q=1}^Q \gamma_q R_q(\phi_q(\mathbf{x}_q)), q = 1, \dots, Q. \quad (9)$$

In this paper, the overall reliability of  $K$  infrastructures are discussed where the formations of the infrastructures are assumed to be idealized. Some effects such as environmental, time and random effects are not considered in the basic infrastructure set up. We investigate four possible scenarios for the overall reliability of the  $K$  infrastructures which are not formative only. For simplicity and without loss of generality, the scenarios under series operation between the infrastructures are studied.

### A. Geographically-weighted Model

Geographic locations of the infrastructure usually affect the reliability of an infrastructure and the overall reliability of the main platform. As an instance, performance of a set of infrastructure may vary in different climates or environments. The overall reliability with geographical weight  $g$  is modelled as below,

$$R_K^g(\mathbf{X}) = \sum_{k=1}^K g \gamma_k R_k(\phi_k(\mathbf{x}_k)), \quad (10)$$

where  $0 \leq g \leq 1$ .

### B. Spatial Model

Spatial effect in this context is referred to the formation of the infrastructures in respect to each other while the serial reliability may be affected by spatial location of every consecutive infrastructure e.g., distance between infrastructures. Therefore, the overall reliability with spatial correlation is modelled as follows

$$R_K^{sp}(\mathbf{X}) = \sum_{k=1}^K (1 - \rho_{k-1,k}^2) \gamma_k R_k(\phi_k(\mathbf{x}_k)), \quad (11)$$

where  $\rho_{k-1,k}$  is the spatial correlation between  $(k-1)^{th}$  and  $k^{th}$  infrastructures.

### C. Temporal Model

Infrastructures may perform differently over time. The performance and reliability of an infrastructure can also be affected by its operating time. The element of times should be also considered in the calculation of the overall infrastructures reliability by indexing the time. The temporal model for  $K$  infrastructures reliability is thus

$$R_K^t(\mathbf{X}) = \sum_{k=1}^K \gamma_k^t R_k^t(\phi_k(\mathbf{x}_k)). \quad (12)$$

This model can be assumed as either stationary or non-stationary. Moreover, it can be extended to an auto-correlative model in which there time lag trend effect is also considered.

### D. Mixed-effects Model

All the above mentioned influential effects are measurable. In practice, there is a number of effects among interactions between the infrastructures that are not measurable or observable or hard to measure in terms of accessibility and cost. These effects can be defined as random effects or mixed-effects between the infrastructures so that we can model the overall reliability of the  $K$  infrastructures as below

$$R_K^M = R_K(\mathbf{X}) + \mathbf{INF}, \quad (13)$$

where  $R_K(\mathbf{X}) = \sum_{k=1}^K \gamma_k R_k(\phi_k(\mathbf{x}_k))$  and  $\mathbf{INF}$  is the vector of random effects defined for the  $K$  infrastructures. These random effects are to be predicted using statistical modelling and estimating techniques [6]. This way, the vector of random effects is assumed to distribute symmetrically around zero.

### E. Hybrid Model

Here we proposed and briefly reviewed some possible and common scenarios in infrastructure reliability analysis. These scenarios can be combined for example if the reliability of an infrastructure is to be calculated considering both spatial and temporal effects. In such a case, a Spatio-Temporal model can be used for calculating the desired reliability. These combinations are generally considered as a hybrid model. Note that random effects can be included in any type of reliability models presented in this study.

## IV. Conclusion and Future Research

In this paper we presented a general framework of the infrastructure reliability based on a two-fold nested structure. We assumed a simple model and a structure function to investigate the interaction of  $K$  infrastructure in terms of performance and reliability. Moreover, a few complicated models for interactions of the infrastructures are reviewed. In future studies, complex and hybrid models should be evaluated using both numerical and graphical techniques. Employing the advanced statistical reliability methods such as nonparametric and Bayesian methods to obtain more accurate reliability estimates is the direction for future research.

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# Using Smartphones to Estimate Road Pavement Condition

Viengnam Douangphachanh<sup>a</sup>  
Hiroyuki Oneyama<sup>a</sup>

**Abstract:** Efficient road infrastructure maintenance and management depends on many factors, of which the availability of updated pavement condition data is among the most important. Today's smartphones, which usually come with many sensors, are potentially useful tools for pavement condition estimation. This paper explores the use of data from smartphones' accelerometers to analyze for features and relationship of acceleration vibration to estimate road roughness condition. Although, the estimation might not be as accurate as modern profilers, it still may be very useful for cost saving and as an indicator for continuous monitoring. In the experiment, smartphones are placed inside vehicles and drive along selected road sections to gather data for analysis. The analysis consists of data filtering, matching with location and reference data, sectioning and frequency domain analysis. Results show that acceleration vibration magnitude has a linear relationship with road roughness condition.

**Key words:** Smartphones; Road Pavement Condition; Pavement Condition Estimation; Road Roughness

## I. Introduction

Road pavement condition can be defined by the irregularity, which may be in the form of surface unevenness, potholes, cracks, deterioration or damages and so forth, in the pavement surface that adversely affects the ride quality of vehicles. Road roughness is an internationally accepted indicator to which it is usually used to measure the condition of road pavement. Roughness is an important pavement characteristic because it affects not only ride quality but also vehicle delay costs, fuel consumption and maintenance costs. The International Roughness Index (IRI) is a measurement indicator that has been used internationally for road pavement condition<sup>1</sup>.

Bad pavement condition can cause; damage to vehicles, may increase fuel consumption, increase road user costs for vehicle maintenance, reduced driving comfort, and sometimes it may pose a significant traffic safety threat to road users. Therefore, pavement condition information is usually of the interests of the general public, road users and particularly the government or road

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<sup>a</sup> Graduate School of Civil and Environmental Engineering, Tokyo Metropolitan University, Hachioji Tokyo 192-0397, Japan, [douangphachanh-viengnam@ed.tmu.ac.jp](mailto:douangphachanh-viengnam@ed.tmu.ac.jp)  
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authorities. For the authorities, the information is crucial in their decision making process especially for strategic planning such as management planning, maintenance planning and programming of the road infrastructure. The lack of sufficient availability of funding, technology and skillful manpower often leads to infrequent collection of pavement condition data, thus the data is usual left outdated. Consequently, sound management and maintenance of the road infrastructure have often been compromised, which is usually viewed as a great challenge for many road authorities in maintaining good quality of road infrastructure under budget constraint, particularly in developing countries.

Using smartphone as a tool to collect data is a promising alternative because of its low cost and easy to use features in addition to its potentially wide population coverage as probe devices. Smartphones nowadays usually come with many useful sensors. Accelerometers and GPS are among many sensors that can be found in today's smartphones. Many researchers have proposed approaches that use smartphones to detect road anomalies in the hope of increasing the ability of road authorities to collect data at an appropriate frequency, required for management and maintenance planning. Noticeably, the majority of these studies focus mainly on identifying and locating road anomalies such as bumps, potholes, cracks and so forth. One of the final aims of our research, however, is to focus on the use of smartphones to estimate pavement condition (roughness) based on IRI, which is different from the previous researches. Being able to obtain roughness condition data of the pavement by an easier mean, road authorities would understand more thoroughly about the condition of their road network. Thus, be able to make better plans for road network management, maintenance and monitoring. To achieve our final goal, this paper explores features and the relationship between smartphone sensor data, collected by accelerometer and GPS, and road roughness condition (IRI). Such information would enable us to develop a smartphone application with simple algorithms or models that can be used to evaluate or estimate road roughness condition.

## **II. Related Work**

Using smartphone and mobile sensors to detect road bumps and anomalies has been studied and proposed for pavement monitoring and management purposes in recent years. Previous work that is most relevant to our research includes: the experiment conducted by Gonzalez et al.<sup>2</sup>, through simulation, mobile accelerometers can be used to assess road roughness condition. The Pothole Patrol<sup>3</sup>, a system that also utilizes mobile accelerometers has been developed to successfully detect road anomalies. Mohan et al.<sup>4</sup> used many sensing components from mobile phones such as accelerometers, microphones, GSM radio, and GPS to monitor road and traffic conditions. By analyzing data from the sensors, potholes, bumps, braking and honking can be detected. The information is then used to assess road and traffic conditions. In some studies<sup>5-6</sup> Android smartphone devices with accelerometers are used to detect location of potholes. Their approach includes many simple algorithms to detect events in the acceleration vibration data. Analyzing data obtained by smartphone accelerometers in frequency domain to extract features that are corresponding to road bumps is carried out in the work of Tai et al.<sup>7</sup> and Perttunen et al.<sup>8</sup>

## **III. Methodology**

Different road pavement conditions cause passing-by vehicles to vibrate differently. We assume that the vibration can be recorded by placing smartphones, which come with accelerometers, somewhere inside the vehicle. In our experiment, we place two smartphones on four different vehicles (one vehicle at a time). Under normal driving conditions, we drive each experiment vehicle along many selected roads that have different pavement conditions, with condition indexes ranging from good, fair, poor, and bad, respectively based on IRI, See Table 1 below. Two different sensors on the smartphones are set to record acceleration and GPS data. To simplify our experiment, the orientation of the smartphones is fixed. Thus, we assume that the acceleration coordinates of the vehicle and smartphones are the same. A video camera is also used to capture the road surface; this video footage is used for data checking and verification if required.

A Vehicle Intelligent Monitoring System or *VIMS*<sup>9</sup> is also used to estimate condition (IRI) of the roads selected for our experiment. Results from *VIMS* are used as reference road roughness condition data. The experiment was conducted in Vientiane Capital City, Lao PDR, from 16 to 21 November 2012.

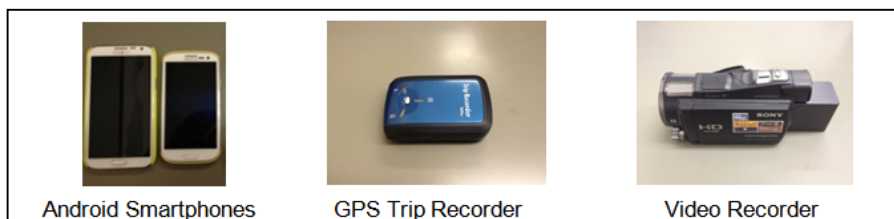
**Table 1. Pavement Condition Index**

Condition Index	Average IRI
Good	$0 \leq \text{IRI} < 4$
Fair	$4 \leq \text{IRI} < 7$
Poor	$7 \leq \text{IRI} < 10$
Bad	$\text{IRI} \geq 10$

#### IV. Data Collection

##### A. Equipment and Software

The main equipment for our experiment is shown in Figure 1 below:



**Figure 1. Experiment equipment**

The experiment equipment included: two Android smartphones (a Samsung Galaxy Note 2 and a Samsung Galaxy S3), a GPS logger and a video recorder. In order to collect the required data, we installed an application called “AndroSensor“, AndroSensor<sup>10</sup> on both smartphones. AndroSensor can collect data from almost all of the sensors available on the handsets and it is available for free download in the Google Play Store. However, for this experiment, only acceleration data (x, y, z) from the accelerometer, and location data (longitude, latitude, and speed) from the GPS were needed. A recording rate of 0.01 second interval or 100Hz was used.

Four Toyota vehicles, a VIGO 4WD pickup truck, a VIGO 2WD pickup truck, a Vios sedan, and a Camry sedan, were selected for our experiment.

### B. Referenced Road Roughness Condition Data

*VIMS* was used to obtain the referenced pavement condition data used in this study. *VIMS* is developed by The Bridge and Structure Laboratory at the University of Tokyo, Japan. The system is now being deployed for road management purpose in Laos. For our experiment, *VIMS* was used with the experiment vehicles. To use *VIMS*, proper calibrations are carried out, details can be found in *VIMS*<sup>11</sup>. *VIMS* data collection for the four vehicles is carried out at the same time of the smartphone data collection.

*VIMS* uses an accelerometer and a GPS on a vehicle. The vehicle then drives on a road and calculates the International Roughness Index (IRI) in a short time based on acceleration response of the vehicle. *VIMS* calculates IRI for every 10 meter road section. The result can be put in an Excel spreadsheet as well as output to a visual presentation on Google Earth. *VIMS* can only calculate IRI when driving speed of experiment vehicle is 20kph or faster.

### C Data collection setting

The two smartphones were glued closed to each other on the dashboard of the experiment vehicles with strong and thin adhesive tapes. The screens of the smartphones are facing up and the heads point towards the front of the vehicle. Therefore, the x, y and z axes of the accelerometer represent the motion along left-right, front-rear and up-down of the vehicle, respectively. Other equipment such as GPS and video camera are also placed on the dash board. *VIMS* components are also installed in accordance to the *VIMS* manual<sup>11</sup>.



Figure 2. Data collection setting



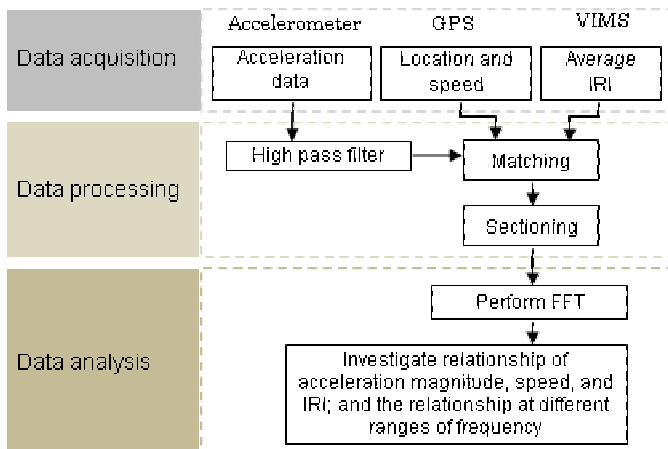
## V. Data Processing

After data from smartphones was uploaded onto a desktop computer and converted to excel spreadsheets, validation checks were carried out. The validation is to ensure that only road sections that have complete data sets, both data from smartphones and IRI data from *VIMS*, will be selected for further analysis. Sections with incomplete data are the sections that have no data from smartphones and/or *VIMS*, that is when the vehicle speed is too slow (<20kph) (i.e in heavy traffic conditions).

A high pass filter, a standard method used for Android device, Android Developer Reference<sup>12</sup>, is applied to remove unrelated low frequency signals, which are usually caused by the effect of vehicle motion as the result of changing speed or turning, as well as the contribution of the force of gravity, from all axes (x, y and z) on the acceleration data.

Data matching by GPS coordinates is carried out. This process merges two separate data files, IRI data from *VIMS* and the acceleration data from the smartphones for the same road sections based on GPS coordinates, to form a new data file. Then, the new data files are cut into small 100 meter sections. A 100 meter length of acceleration data is chosen as a unit for road surface estimation in this study. The reasons are (i) because Road Management System in Laos requires road surface condition to be estimated for every 100 meter section, therefore it would be more convenient for us to select the same unit so that it is compatible for future application; (ii) there is a concern on the accuracy of GPS position data, thus choosing a shorter section unit may cause some issues for data matching between *VIMS* and smartphone GPS data. In the sectioning process, road sections where the experiment vehicles stopped (checking from speed and *VIMS* results) are excluded as data from these sections cannot be used to estimate road roughness condition. In addition, sections that are less than 100 meters are also ignored.

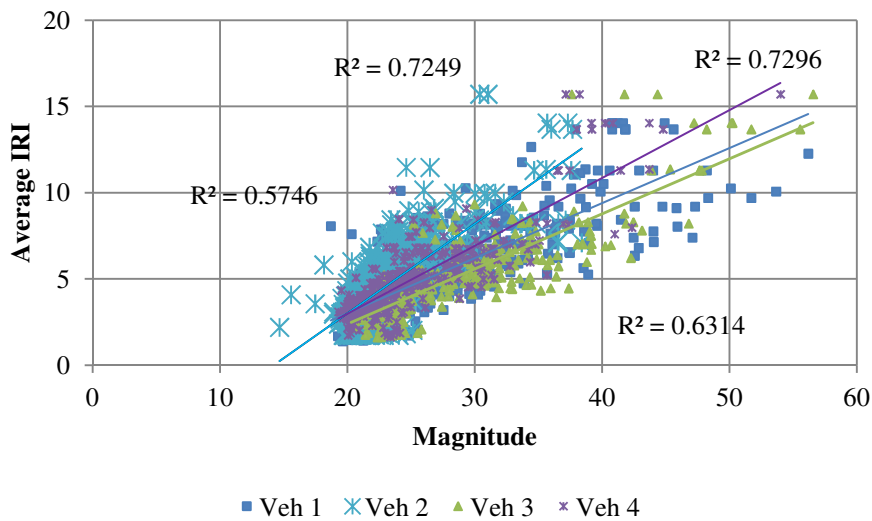
All selected data sections are converted to the frequency domain and Fast Fourier Transform (FFT) was performed. Magnitude from FFT is the amplitude or strength of the associated frequency component. For a specific frequency window, we assume that the total sum of magnitudes represents the total strength of the vibration at that frequency window. Therefore, the sum of magnitudes from FFT is studied to locate features, and examine the effect and relationship that the acceleration data might have in connection with road roughness condition.



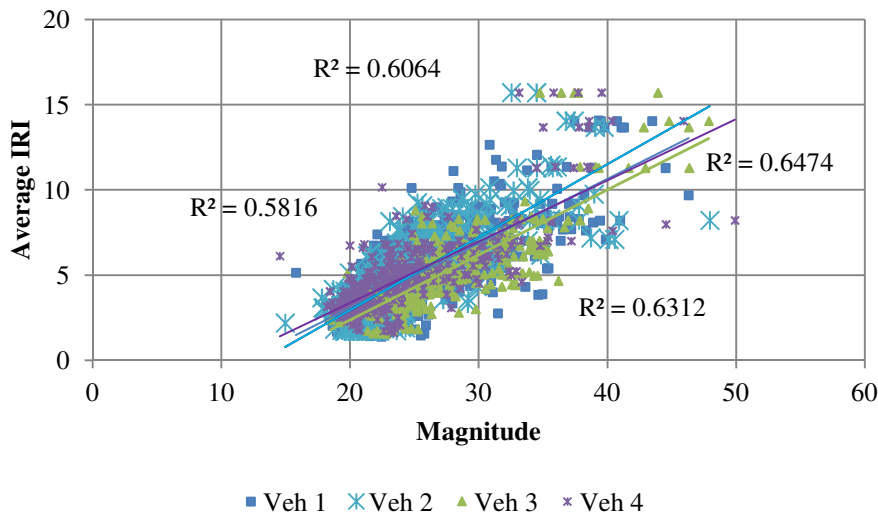
**Figure 3. Data processing flow chart**

## VI. Analysis and Results

From the analysis, we have found that acceleration data has linear relationship with road conditions. The correlations between the sum of magnitude of the acceleration data and average road roughness (IRI) for all devices and all vehicles are shown in figure 4, 5, 6 and 7 below. An average IRI is calculated from 10 *VIMS* IRI values (*VIMS* calculates IRI for every 10 meter road section) that comprises into a 100 meter road section. The sum of magnitudes is the total magnitude derived from FFT of the sum of acceleration x, y and z in 100 meter road sections.

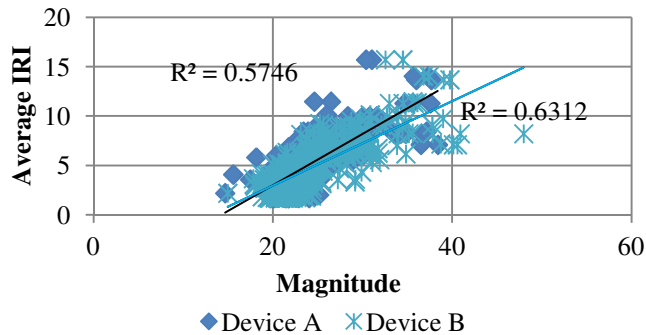


**Figure 4. Relationship between acceleration data and road condition (Device A, Vehicle 1, 2, 3, and 4)**

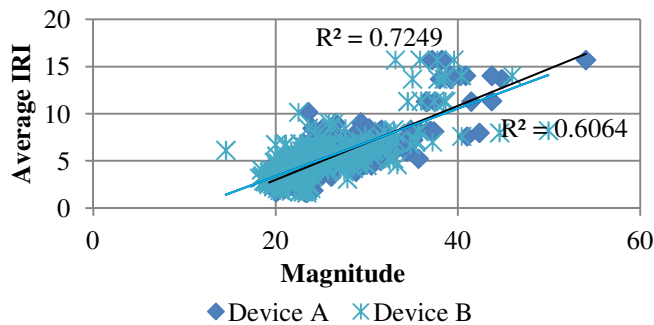


**Figure 5. Relationship between acceleration data and road condition**

(Device B, Vehicle 1, 2, 3, and 4)



**Figure 6. Relationship between acceleration data and road condition (Device A and B, Vehicle 2)**



**Figure 7. Relationship between acceleration data and road condition (Device A and B, Vehicle 4)**

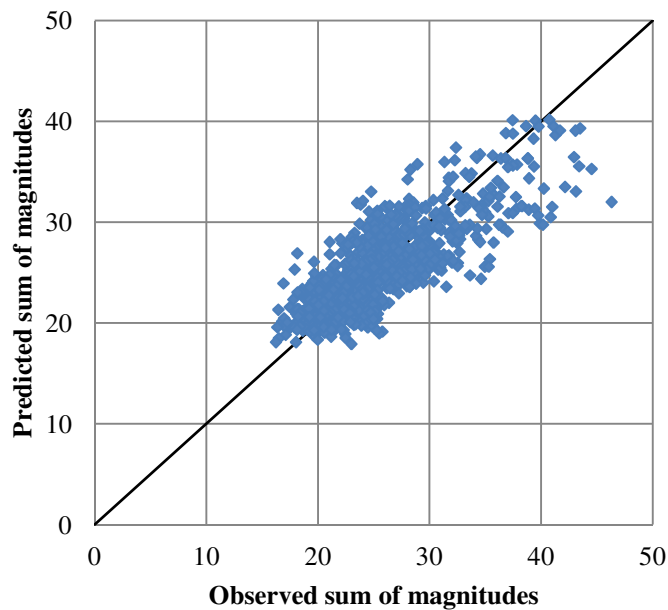
From the graphs above, it can be noted that the significant of relationship between acceleration data and road condition is slightly different between the vehicles and devices. From a statistical investigation, it is also found that the ability to estimate road roughness from acceleration data also slightly depends on the average travel speed of the vehicle.

**Table 2. Summary of multiple regression analysis**

Device A								
	Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
Observations	703		497		314		408	
Multiple R	0.797		0.759		0.855		0.852	
R Square	0.635		0.577		0.731		0.726	
Adjusted R Square	0.634		0.575		0.729		0.725	
F Stat	609.790		336.571		421.594		537.113	
	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat
Intercept	-2.467	-5.868	-6.476	-8.756	-3.484	-5.893	-5.651	-9.096
Magnitude	0.305	28.820	0.498	20.757	0.311	23.603	0.409	24.678
Avg. Speed	-0.013	-2.733	-0.010	-1.578	-0.007	-1.048	0.008	1.391

<b>Device B</b>								
	Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
Observations	674		489		319		411	
Multiple R	0.774		0.798		0.805		0.779	
R Square	0.599		0.638		0.647		0.607	
Adjusted R Square	0.598		0.636		0.645		0.605	
F Stat	501.448		427.417		290.138		314.653	
	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat
Intercept	-2.423	-4.929	-4.317	-7.604	-5.348	-6.918	-3.482	-4.835
Magnitude	0.341	24.595	0.403	23.684	0.383	19.531	0.352	17.879
Avg. Speed	-0.027	-5.415	-0.016	-2.905	0.001	0.106	-0.003	-0.528

It has been observed that the multiple regression yields a very good fitting (Figure 8). As summarized in Table 2, the intercept and coefficient of the average IRI and average speed are statistically significant. The coefficients of the average IRI is positive, meaning that the worse the road surface condition is, the larger the sum of magnitudes of vibration. On the other hand, the coefficient of the average speed is negative. This implies that a speed increase would mean a smaller sum of magnitudes, which could mean better road surface condition. One of the reasons could be, however, in general, drivers tend to drive at a higher speed on good roads; and at a much slower speed on road with bad surface condition. In addition, although the order of the coefficients is very similar for all devices and vehicle, the difference of coefficient by vehicle type and devices is observed.



**Figure 8. Performance of the multiple regression model**

To sum up, from our analysis, it is clear that IRI can be expressed roughly as a linear function of magnitude of acceleration vibration and average speed of the vehicle. Parameters (coefficients) of linear function are different representing different vehicles and devices.

## VII. Conclusion

The main objective of this paper is to explore the use of smartphones for road infrastructure management and maintenance purposes. Rough estimation of road pavement condition from smartphones would be helpful enough for such purpose, provided that the approach is low cost, easy to operate and can be implemented frequently.

After obtaining data from our experiment, processing and analysis, it has been found that acceleration data from smartphones has linear relationship with road roughness condition. However, the significant of relationship depends on the average speed of vehicles. We conclude that a simple model would be sufficient to estimate road roughness condition from acceleration data obtained by smartphones. In our future studies, more realistic setting of smartphone devices, free orientation, will be considered.

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# Connected Mobility Digital Ecosystem: A Case Study on Intelligent Transport Analytics

Edward Dou<sup>a</sup>  
Peter Eklund<sup>a</sup>  
Tim Wray<sup>a</sup>  
Chris Cook<sup>a</sup>  
Vu The Tran<sup>a</sup>

**Abstract** The UOWShuttle\* is a transport app that provides users with real-time bus location and predictive information from *Automatic Vehicle Location and Automatic Vehicle Counting* systems. The system anonymously tracks interactions within the transport network. This paper is a briefing document on the analytics of the Connected Mobility Digital Ecosystem project, of which the UOWShuttle forms an important part. It describes its overall system architecture and gives some of the statistics of some of the data collected to date.

**Key words:** Location-Based Services; Intelligent Transport Application; Digital Ecosystem.

## I. Introduction: Location-based Services

In this research we concentrate on a public transport passenger tracking application for a free shuttle bus network shown in Figure 1. This location data can be used to provide value-added services to the users and manage system transport behavior including optimization of the transport resources and maximizing passenger comfort. While there are many issues in relation to the use of location-based applications, none are focused on as prolifically as the issue of privacy. Vicente, Freni, Bettini and Jensen<sup>1</sup> and Rose<sup>2</sup> claim that the most common way that information is released through these applications is by the users themselves. This is the approach adopted in our design with users opting in to having their location data recorded.

When considering location-based apps there are three main issues highlighted in the literature. These are the *categorisation* of applications, whether they are location tracking or location aware; the *architecture* of applications: including the location sensing technique and system architecture and thirdly matters of *privacy*. In our architecture, the clients are anonymised but each is allocated a unique identifier – related - but not identical - to the UUID of the users' device. This allows us to track when a device interacts with the transport network via the client app. We recorded the time, location and whether the passenger has joined a free bus and we can determine where they alight via an automatic passenger counting (APC) system that is installed

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<sup>a</sup> Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

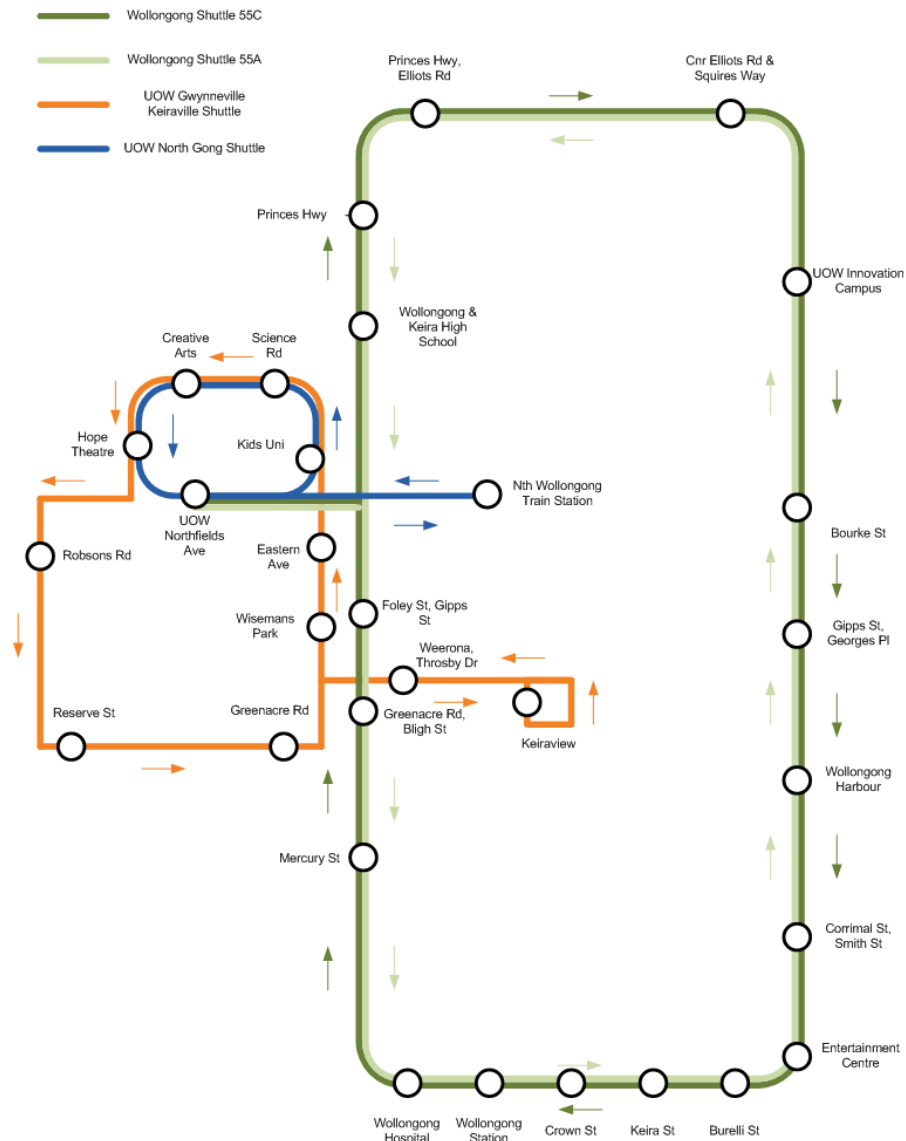
\* The UOWShuttle app was written by Edward Dou and published by the Centre for Digital Ecosystems in November 2011. The UOWShuttleV2 app has undergone several improvements: version 2.3 of the UOWShuttleV2 app was published in September 2012.

<http://dx.doi.org/10.14453/isngi2013.proc.1>

on the doorways of all the shuttle buses in the fleet. We have no way of knowing the identity of the user but via this method we can determine if the same user interacts with the system multiple times.

### A. System Architecture

In our system (Figure 2), the transport tracking system consists of four major components: on-board unit, which is installed on a vehicle (a bus); a vehicle presence server, responsible for receiving and processing data from on-board unit and saving it to the database server; a web server, which provides web services to the end users and matches data to a map; and finally a native iPhone application (the UOWShuttle client) for presentation to users.

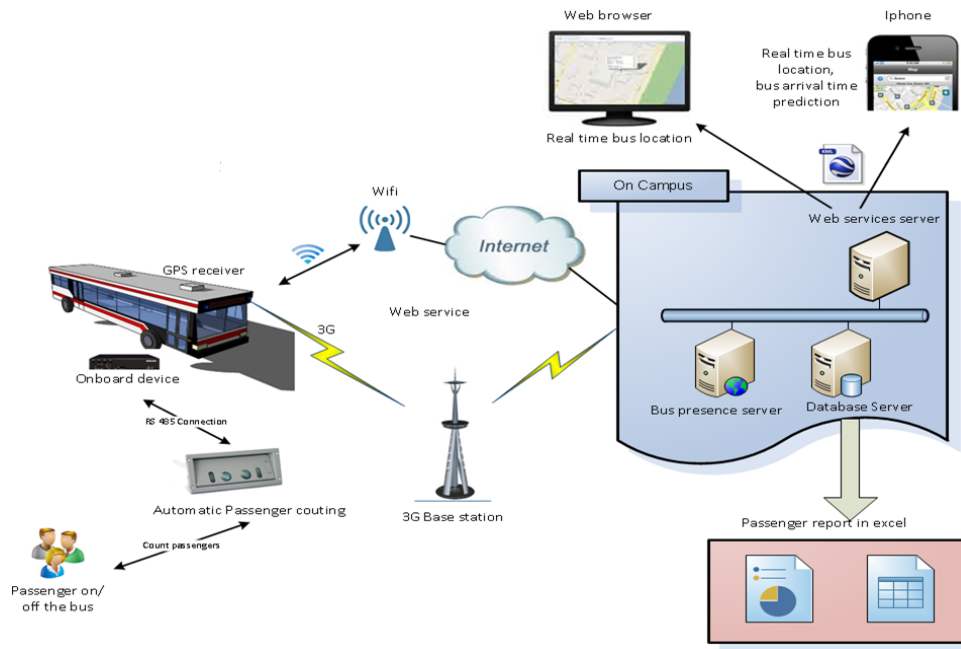


**Figure 18. The Free Bus Network around the University of Wollongong forms the basis for the Connected Mobility Digital Ecosystem case study.**



## B. On Board Unit

The function of the in-vehicle device is to transmit shuttle bus's GPS coordinates and passenger usage information to a central server using a 3G cellular data link. The in-vehicle device also acts as a Wi-Fi hotspot. The Wi-Fi hotspot is a way of extending the digital footprint of the client by determining if their UUID is involved with sessioning via the app and/or connecting to the hotspot after boarding the bus. A central location server receives location updates from all in-vehicle devices and all buses in the fleet instrumented in this way.



**Figure 19. A Schematic of the Connected Mobility Transport Application Architecture.**

The individual transactions are put through batch- and online processing. In batch mode, the vehicle GPS tracks are produce historic route timings, stop locations, and actual bus schedules. The bus passenger information produces daily passenger usage data. Online processing matches vehicles to routes, and performs arrival time prediction. An in-vehicle computer with built in GPS, 3G mobile and Wi-Fi is installed on the all buses in the fleet. A customized Linux OS with MySQL and Python is install on the system and is configured as a Wi-Fi hotspot. Internet access is provided to the passengers' device through the 3G data connection. An embedded application is also developed and installed on the in-vehicle unit. Its main purpose is to:

- Capture the bus location.
- Capture relevant bus passenger information.
- Upload information to location server through the 3G connection.
- Monitor data capturing and transmission processes, ensuring the processes are functioning at all times.
- Monitor vehicle ignition for automatic system shutdown.

The following data capturing and transmission strategies are made:

After the system starts up and a 3G-connection is established, it establishes a secure SOAP/HTTPS link to the location server on campus.

Vehicle GPS coordinates, speed and heading are captured from a GPS unit and saved locally every second. This data is also uploaded to the vehicle presence server every 10 seconds through a secure link.

When passengers' Wi-Fi devices register and de-register with the in-vehicle hotspot, the GPS coordinates and time stamp of these events as well as the UUID derived unique identifier are captured.



3.

**Figure 3. Passenger Usage Statistics for the Free Shuttle Bus Network at the University of Wollongong**

The digital footprint of the passengers using the transport network is an important idea in the project. The challenge of capturing data about passenger movements is that the buses are free of charge. There are no tickets and therefore no knowledge of where passengers get on or off, as there would be in a ticketed transport system. Therefore, the question is how to automatically capture passenger movements via their interaction with technology on the buses. Capturing a digital footprint allows us to monitor trends in behavior over time and cross-reference the digital footprint with physical passenger behaviors as the technology adopts over time.

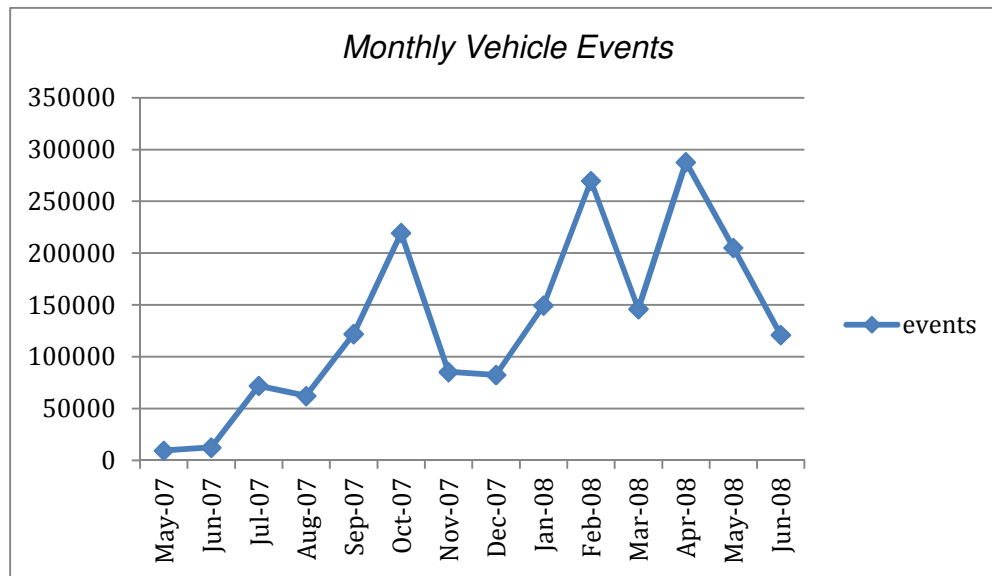
The passenger digital footprint is recorded in three ways. Firstly, by the number of passengers connecting to the on-board free Wi-Fi via a record of their UUID, secondly via the session data captured from the use of the transport app and thirdly via Automatic Passenger Counting (APC) devices installed on the bus doors.

In total, there are an average of 6,000 passenger events per month captured via IP and session tracking. The current number of app sessions recorded per month is between 7,000-14,000 during the peak University teaching session and between 3,000-4,000 during vacation breaks. Not surprisingly, there is a correspondence between the use of the app and connections to the on-bus Wi-Fi. The average number of APC transactions – passenger on/off events – is 8,500 per month.

### C. Location Server Description

A LAMP setup (Linux, Apache, MySQL, and PHP) is installed on a campus-based server. The server performs following functions:

1. Accepts secure SOAP connections from shuttle buses.
2. Receives bus location data and bus passenger data through the secure SOAP link and stores this information into the MySQL database.
3. Processes bus travel timing information from the historical data and categorizes them into bus routes with 15 minutes segments.
4. Processes passenger UUID derived unique identifies and passenger counter information, maps these to the bus stop and scheduled trip information.
5. Predicates arrival information using current and historical data.
6. Provides current bus location and predicated arrival data.
7. Provides a Web interface to display the tracked vehicles.
8. Generates daily passenger usage reports for management.
9. Stores UOWShuttleV2 app usage information.



**Figure 4. Monthly Vehicle Events**

### D. The Data Warehouse

The quantity of data collected by the project is already vast. The bus location data is updated to the server every 10 seconds for all the buses that are running at any one time. So far – as end of July 2013 – there were a total of 1,844,964 vehicle (bus) location events stored in a MySQL database on our servers. The average monthly number of vehicle events captured is 132,000.

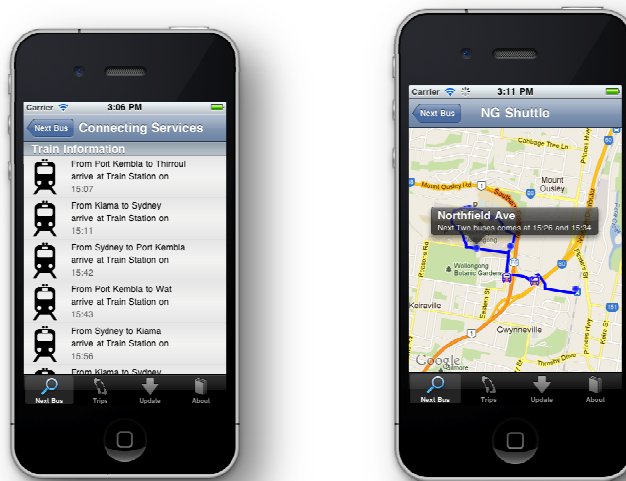
### E. The App: UOWShuttlev2

UOWShuttlev2 is a native iOS iPhone app as is shown in Figure 5. It provides a location aware application for accessing real-time bus arrival information. It contains a ‘table view’ of stops for different routes with a counting down arrival time, a ‘map view’ showing the location of the user and the buses and a ‘saved favourite trips’ view. Usage statistics such as session time, user location and the UUID-based identifier of the iPhone are sent back to the server and stored.

## II. Conclusion

This paper describes the UOWShuttle app that provides users with real-time bus location and predicative arrival information from an *Automatic Vehicle Location* system. In return, the system tracks and warehouses user interactions with the app and within transport network. This paper gives a brief account of the data being collected for the project. The interactions between the physical and digital environments of the connected mobility system are complex enough to categorise the system as a digital ecosystem.





**Figure 5. UOWShuttlev2 iPhone app: Nextbus, Map and Trip view screens.**

### Acknowledgements

This research has benefited from many individuals who have worked on the project, only a few of whom are acknowledged as co-authors. The project was supported by a cash grant from the CSIRO National ICT Centre and from the Australian Federal Government Award for Smart Infrastructure Research.

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# A Mobile Based Integrated Outage Management System

Nampuraja Enose<sup>a</sup>

**Abstract:** This paper proposes an integrated outage management system based on mobile technology for managing utility outages to deliver an agreed standard of service (sos). This outage management system is built on the needs of a utility on client-server architecture. The client application (preferably mobile based) allows users to log an outage complaint with details like location, time of detection, type of outage and extent of outage. The application has built-in menus to narrow down to the closest relevance and also permits inclusion of other details using sophisticated mobile applications. Each complaint is uniquely tagged and directed to the server. The server application is built on a layered architecture that can intelligently assign it to the respective group which has an identified owner, based on the details like type of utility, location, time etc. All the child complaints are identified with the parent complaint making it easier to handle. The intelligence and analytics layer identifies the parent-child relationship and other relationships where cross-sector relationships are involved. This intelligence therefore makes an integrated outage management system for all infrastructure services. This application can also be enhanced to monitor social media interactions to capture outage discussions. The mobile based application makes it easier for the customers to quickly log a complaint and track its status real-time. The other benefits of this system include: reduced outage durations, faster restoration based on location predictions, reduction in outage frequency, accurate and real-time outage and restoration information, extended asset and service life, reduction in customer complaints and improved customer satisfaction.

**Key words:** Public infrastructure; Integrated systems; Monitoring and control; Outage management; Mobile technology; Layered architecture

## I. Introduction

The public infrastructure, the combination of fundamental systems, which is made up primarily of water utilities, sewer lines, electricity grids, telecommunications, transportation and housing, has a large impact on society. It is fundamental for economic prosperity and plays a vital role in determining quality of life. Therefore, one of the key responsibilities is to ensure a good public infrastructure and efficient infrastructure management that can boost productivity and growth that keeps the economy healthy. At the same time, it is no secret that most of this infrastructure was built in the 20th century and is aging and failing, and the utilities are struggling to efficiently manage them, especially their lack of reliability, safety and efficiency. While there has been huge investment to improve the physical infrastructure, comparatively less attention has been paid by the majority of the utilities in managing the systems and maintaining

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<sup>a</sup> nampuraja\_enose@infosys.com Centre of Innovation for Tomorrow's Enterprise (CITE), Infosys Labs, Infosys Limited, Bangalore, 560100, India.  
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the services they promise to deliver. In fact, most of the utilities still manage and control the existing infrastructures with manual processes. On the other hand, the changing climatic conditions, rapidly increasing population, disruptive technology adoption, the quest for sustainability and critical need to improve living standards is turning the spotlight firmly on building advanced infrastructure as an essential component of a comprehensive economic strategy. This is building up massive networks of intelligent infrastructure systems, with information and sensing technologies with complex interactions and interdependencies between individual systems. The systems for transmitting and processing information have also expanded and complicated the infrastructure network, beginning with telephone lines and now encompassing all sorts of IT and telecommunications systems. Therefore, one of the biggest challenges of the 21st century is to better manage these complex “system of systems” and leverage on their capabilities for improved efficiency and better utility, which is critical for driving and sustaining economic growth.

This paper therefore proposes an integrated outage management system based on mobile technology which leverages the intelligence in infrastructure systems to help utilities better manage outages and deliver on the agreed standard of service.

## **II. Outage management system**

Outage in critical infrastructures and their associated systems and networks cause interruption of critical services to users. Quite often these infrastructure systems and networks are taken for granted, but a disruption of one of those systems can have dire consequences. In addition, these systems encounter high frequency outages caused by weather, component wear and myriad other reasons, and the need to reduce outages and restoration time has become critically important. However, most of the utility companies are still grappling with outdated paper systems and traditional tools that require a high-degree of human interpretation and manual processing. Therefore, utilities have failed in efficiently managing these systems and maintaining the services they promise to deliver. These concerns along with the constantly growing customer requirements on the quality of service have made outage management systems a critical tool for reducing the magnitude and/or duration of disruption in services.

### **A. Integrated outage management system**

One the principal reasons that some of the issues have not been answered satisfactorily is the lack of harmonised measures in managing the infrastructure and services, reckoning the infrastructure industry as a whole. Infrastructure stakeholders have focused on sector specific solutions thereby significantly missing the impacts and benefits that can be identified by assessing the inter-dependencies between these sectors. An integrated outage management system is therefore aimed at leveraging this unique opportunity by enabling cross-sector interactions between the primary infrastructure sectors and their associated systems. This system is, therefore a first step towards building a unified system that functions collaboratively and synergistically in responding to outages.

## **B. The Architecture**

The outage management system is built on a multilayered architecture that uses different layers for performing the different functionalities of the system. The following layers explain the building blocks of the system in detail.

### **i. User access layer (client application)**

User access layer is where the user can directly log an issue on disruption or outage of a service from a specific service provider - like power blackout, telephone service disruption, sewage overflow and pipeline leakage. This can be initiated using a simple mobile application, which will have a form to open a new ticket. To make it user friendly and to maintain a standard pattern of information detail, a scroll down option would be made available for the different data inputs in the form. The user can, accordingly, fill the form with details like type of service disruption, location details, time of detection, type of outage and extent of outage. The standardization of information increases system usability and field-service productivity. The mobile application has built-in menus to narrow down to the closest relevance and also permits the inclusion of more details using sophisticated mobile applications like image or video. The additional information will provide service engineers with more detail for quickly responding to outages.

The user friendly interface allows the user to quickly open tickets and submit details on the outage. Once the filled form is submitted by the user a complaint ticket with a unique id is generated. The unique ticket is then sent to the data base layer. Any update to the ticket will be made available real-time at the mobile application or updated to the user via his/her preferred mode of communication - SMS or email or both. This overcomes the critical disconnect of lack of real-time field information, with most of the OMS systems today. Some of these systems provide updates based on historical data leading to stale information, leaving a set of frustrated customers who repeatedly have to call back for updated information. Real-time update is, therefore, very critical for users because they not only want to be assured that their utility is aware of their outage, but they also know that someone is working on the problem. Since quite often these are critical service disrupting outages, they also expect real-time information regarding the repair progress, the estimated restoration time and they are quite interested on the cause for the outage.

The user-access layer can also be provisioned to receive public complaints over an SMS, from public bulletin boards or through posts from social networking websites, like Facebook and Twitter. In these cases, these alerts are received by the service desk that can manually open a ticket with the basic details available. Once the ticket is opened, any update on a ticket from the field will in turn be updated real-time back to the users via the respective channels - SMS, public bulletin boards or the respective social networking sites. The service desk can also connect legacy systems and traditional sets of tools like Interactive Voice Response (IVR) and High Volume Call Answering (HVCA) systems.

### **ii. Data base layer**

Data base layer is the centralized database of the integrated outage management system. It is organized to handle large quantities of information by systematically accessing, storing, securing



and managing it. The accuracy of the system completely depends on the integrity of the database layer. The central database performs the following functionalities:

- Logs the user complaint received from the user access layer to the centralized database for all type of services.
- Stores the complete details of customers - the customer database, their location details, the type of services provided, class of customers (if any) and the SLA for different services.
- Stores the details of field service engineers - list of field engineers, expertise level, maintenance schedule, leave calendar and location details.
- Stores the details of infrastructure - the asset database, the unique identifiers, the network mapping, aging of assets and the history of failures.
- Has details of all the services provided by the different infrastructure sectors, the inter-dependencies between these sectors, cross-sector interactions details, maps of service territory, GIS based routing and entire network map. The field service engineers would therefore have access to GIS based digital maps which are up-to-date and enabled with new routing functionality.

This therefore forms the central repository for the outage management system and is the source database for the analytics layer to build intelligent analytic applications using this information.

### **iii. Intelligence & Analytics layer**

The Intelligence and Analytics layer with strong analytical capabilities is the core of the integrated outage management system. It is built with analytical components which intelligently analyses the data retrieved from the underlying database layer and aids service providers and field engineers in quick decision making. The primary function of this layer is to take intelligent decisions by continuously interacting with the relevant data residing at the database layer. As field service functions become more complicated, service providers are today forced to implement real-time field service analytics to maximize workforce productivity, adhere to service-level agreements and achieve service excellence. It performs the following functionalities:

- Analyses the customer tickets to validate if multiple tickets are opened for the same issue/outage.
- Builds outage details as charts and trend lines to explain the dimensions of current outages, the related outages (in case of multiple outages for the same issue) and the cross-sector inter-dependencies between different infrastructure sectors.
- Relates the outages to the network map showing all paths impacted by the outage (calculating database). It shall also show all other outages that impact the path limit(s) for the duration of the outage.
- Analyses the network map and does equipment identification mapping to identify all the equipment IDs/Asset IDs impacted by the outage. Each of the identified equipment is shown on the outage summary display. The Service desk then uses this information to proactively inform the affected customers and details impact and restoration.
- Analyses the outages and calculates the forecasts restoration time/MTTR based on the historical data, SLA's and dimensions of current outages. This enables intuitive reporting.

#### **iv. Administration layer**

Administration layer is the operational layer of the outage management system. It uses the insights provided by the intelligence and analytics layer and executes on them. At administration layer the following set of functionalities are performed:

- The administration layer has a ticket management console/dashboard which is available to the administrator and the field service engineers. Tickets are managed from this console. It also enables alert mechanisms based on the SLAs.
- If multiple tickets are opened for the same issue, a parent ticket is opened and all the related customer tickets are assigned as child tickets to this parent ticket. This could be a single service outage or multiple services affected for a single event, thereby building a cross-sector integrated management system and avoiding duplication of work. Quite often a single event, like an uprooted tree at a public place, could impact multiple services like electricity, telecommunication, transportation, water and sewage lines - which need a single parent ticket to be managed.
- A field service engineer will always work on a parent ticket (if available for an outage) and any real-time update that is done on the parent ticket is, at the same time, updating all the child tickets. This also helps in overcoming the issue of multiple service engineers assigned with different tickets concerning the same issue.
- Tickets are normally self-assigned by the field service engineers to themselves based on their availability and expertise. In case the tickets are in queue and are close to violating the SLA for ticket assignment, the administrator can manually assign the ticket to the most relevant service engineer.
- The admin layer connects with the service desk for real-time updates to the users for those tickets manually opened by them - via SMS, public bulletin boards or the respective social networking sites. The service desk can also connect legacy systems and traditional sets of tools like Interactive Voice Response (IVR) and High Volume Call Answering (HVCA) systems.
- The admin layer is responsible for automations (as applicable) using the insights from the intelligence and analytics layer, for superior application performance.
- The admin layer manages the closure of the tickets. Once the ticket is closed, the closure information along with closure comments is updated real-time in the tickets and therefore with the customer. It is also sends to the service desk to update the customer on the manual tickets opened by them.

### **III. Conclusion**

This is definitely not a system that will eliminate outages. No systems can accomplish that vision. However, this system, when implemented rightly, can increase utilities' ability to identify outages, increase efficiency in prediction, reduce outage response time, forecast restoration times, communicate accurate information to customers and accelerate the pace of repairs. It also makes it a "one-stop" cross-sector solution to handle the outages of different infrastructure systems and their associated networks.

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# **A star schema for utility network analysis and visualisation in a Geo-business intelligence environment**

Sasha Sadegholvaad<sup>a\*</sup>  
Rohan Wickramasuriya<sup>a</sup>  
Jun Ma<sup>a</sup>  
Pascal Perez<sup>a</sup>

**Abstract:** Utility network analysis is an established area of research in Geographic Information Science (GIS), but it is yet to feature in a Business Intelligence (BI) environment. Inclusion of this capability in BI can be achieved by modelling a utility network as a star schema. Star schema, which is a well-known data model used in data warehousing for BI solutions, organizes data into several fact tables referencing one or more dimension tables. This simplifies joins to provide fast execution of queries. Furthermore, star schema enables the analysis of data from multiple angles (slicing and dicing). However, modelling spatial data as star schema is still in its infancy for two main reasons, (a) only very recently have researchers started appreciating the importance of GIS capabilities in BI, (b) specific challenges associated with introducing geometry data with complex topological relationships into star schema. In this paper, we present a star schema to model geometric utility networks such as electricity, water and sewer systems. Our schema provides two-way benefits; it brings in an important new capability to BI in terms of spatial data analysis, and it gives non-technical users an opportunity carry out complex utility network analysis in an easy-to-use BI environment. Finally, we present an application of the star schema in service vulnerability assessment for electricity networks.

**Key words – Infrastructure networks; Business Intelligence; Star schema.**

## **I. Introduction**

Geographic Information Systems (GIS) provides rich capabilities for network analysis resting strongly upon the theoretical basis of the mathematical subcategories of graph (network) theory and topology.<sup>1</sup> Several different methods and techniques are available within graph theory that enables one to describe measure and compare both individual graphs and groups of graphs in order to demonstrate their properties. Most of the mainstream GIS software tends to incorporate various subsets of these techniques in dedicated, domain specific network analysis modules.

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Northfields Ave, Wollongong NSW 2522, Australia

<sup>\*</sup>Corresponding author: E-mail: [ss950@uowmail.edu.au](mailto:ss950@uowmail.edu.au)  
<http://dx.doi.org/10.14453/isngi2013.proc.40>

Network-based applications in GIS are usually geared towards modelling infrastructure networks with which the general public interacts on a regular basis. As long as networks of interest contain geographic elements, GIS tools have the ability to model and map them, for instance transportation, electricity and water networks which are in fact the main interest of this particular study.<sup>1</sup> Transportation network applications of GIS have experienced a significant interest over the last decade. Google Maps and Mapquest internet services are two good examples for such globally used facilities that provide route planning services and location services.

The other area of interest in this study is Business Intelligence (BI) which has traditionally been used by firms to analyse business data with the aim of obtaining Key Performance Indicators of interest.<sup>4</sup> BI possesses powerful tools that can (a) harness disparate data sets in optimized data warehouses and (b) build highly interactive, online accessible reports and dashboard utilizing data stored in warehouses. BI reports and dashboards are easy to understand and use, hence ideal for use as public domain policy support tools. However, BI has traditionally lacked the capabilities to analyse and visualize geospatial data. Thankfully, BI community is realising the importance of integrating geospatial capabilities into BI software, particularly in the face of mounting geospatial data made available by new technologies like satellite remote sensing and Global Positioning Systems.

One of the primary structural components of any BI project is a data warehouse. Star schema is the most common schema design used in data warehouses that could be used to generate multidimensional cubes for BI analytics.<sup>5</sup> The “must use” of star schema to build Online Analytical Processing (OLAP) cubes is one of many reasons that such schema design is preferred over the conventional one. Star schema organises data into one or more fact tables referencing any number of dimension tables. A star schema can simplify join queries and provide capability to analyse data from multiple dimensions, thus enabling a user to perform various drill down, roll up, slice and dice operations on data. Short responding time and processing in the same way that human process data are other advantages of star schema design.

Although star schema has several advantages over conventional normalised schema designs, it still faces challenges when it comes to introducing geometry data with complex topological relationships. Siqueira in his study aimed to tackle one of these challenges and proposed a benchmark (Spadawan) for spatial data warehouses with several appealing, yet imperfect, attributes.<sup>6</sup> Spadawan (a) produces datasets containing points and polygons in spatial characteristics, (b) facilitates the assessment of spatial roll-up and drill-down processes, (c) enables the investigations of spatial data redundancy in spatial data warehouse by providing data schemas with spatial hierarchies and spatial dimensions, and (d) allows the modification of data volume and the spatial attribute selectivity.

Though there have been some attempts to exclusively model spatial data in a star schema, infrastructure networks have not been considered in any of these studies. Given the importance of infrastructure networks to governments at various levels, any BI tool built as a policy support tool needs to be able to store, analyse and visualize data related to infrastructure networks. Hence, the objective of this study is to design and demonstrate a star schema that can store

spatial topological networks in a data warehouse to support network-based analysis in a BI environment.

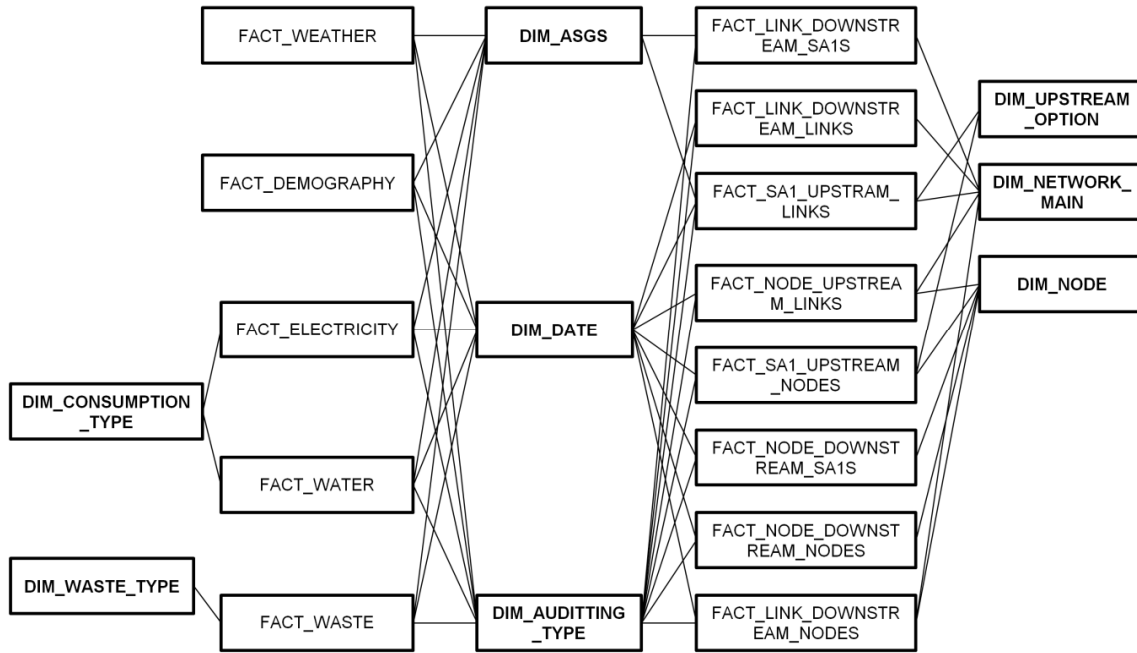
## **II. Design of network star schema**

We designed the network star schema in a way that it can be connected to other schema available in the data warehouse using common dimension tables. Figure 1 illustrates the generic network star schema that we designed and its association with another schema that is designed to capture utility use (e.g. electricity, water) at geographic areas defined by the Australian Bureau of Statistics (ABS) in 2011.

The dimension table models the geographic hierarchy adopted by ABS in its 2011 census. This dimension table also supports postcode-based analysis. Note that this dimension table contains polygon geometry fields to store spatial extents of each census area. The dimension date models the date based on the ordinary calendar and the Australian season and financial calendar. This dimension enables multi temporal analysis of utility consumption. The fact table weather models temperature and rainfall derived from Bureau of Meteorology (BOM) daily records. The fact demography models demographic information extracted from and generated based on ABS census results.

In our data warehouse, each utility networks is modelled using a separate star schema. Figure 1 depicts a generic network star schema. The network schema consists of 10 fact tables and 7 dimension tables. DIM\_Network\_Main and DIM\_Node tables contain the geometry data associate with links the nodes, respectively, in the modelled infrastructure network. This schema allows the user to perform several types of analysis: tracing upstream or downstream from a node or link, querying all geographic areas served by an asset, querying all assets linked to a given geographic area, and running what if scenarios such as finding all affected geographic areas given the failure of a particular asset.

To populate the network star schema with appropriate data, we relied on ArcGIS desktop GIS software. First, the directionality of the network flow was assigned to links. A python script was written to loop through all the elements (links and nodes) of the directional network in order to generate upstream/downstream links, nodes and geographic areas served.



**Figure 1: Overview of the star schema used in SID.**

### III. Star schema in action

In this section, we briefly explain one application of the network star schema that we designed. Service vulnerability is a critical aspect of infrastructure network management. Hence, tools that allow planners to perform service vulnerability assessments on infrastructure networks are invaluable. We built a map-based dashboard that enables planners to perform this kind of analysis on an electricity network modelled using our network star schema (Figure 2).

In Figure 2, blue bubbles represent electricity substations while conductors are represented as red lines. Hovering over a substation reveals ancillary information (such as asset ID and operating voltage) about the substation. Clicking on a substation brings up a drill through report, which again is map-based, that illustrates potentially affected postcodes given a failure of the selected substation. By hovering over any postcode in the drill through report, the user can reveal information such as total annual residential and commercial electricity usage and total population for that postcode (Figure 3).

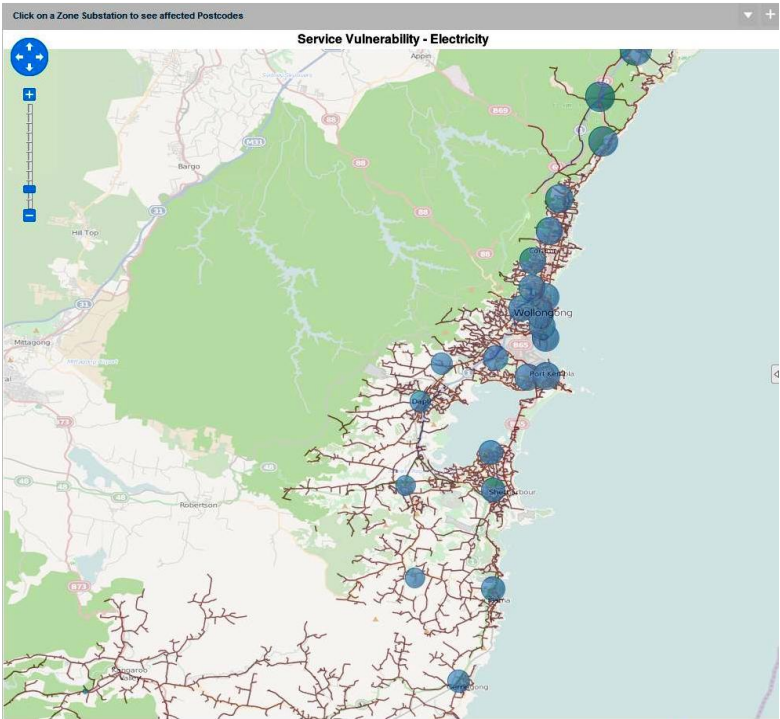


Figure 2. Map-based dashboard for service vulnerability assessment.

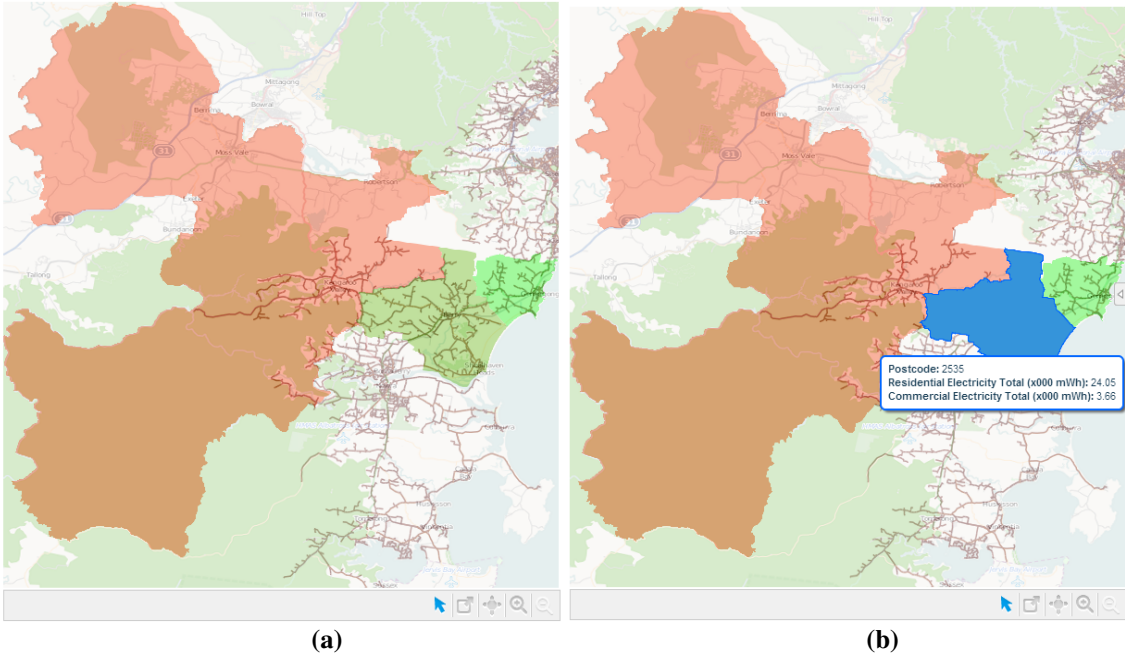


Figure 3. Postcode level affected area maps (a) Postcode map only; (b) Postcode map with demographic and electricity consumption usage details.



#### IV. Conclusion

Network analysis is a useful tool for infrastructure network management. Geographic Information Systems (GIS) traditionally incorporated capabilities to perform advanced network analysis. To use network analysis in GIS software, a user must possess advanced knowledge and skills. Even for advanced users, these capabilities are available in desktop GIS packages, limiting the usefulness of such analysis.

Business Intelligence (BI) software, on the other hand, consists of tools that are easy to use and understand, accessible through internet, and able to build visually rich, highly interactive content. BI is originally developed as a concepts and tools to generate Key Performance Indicators (KPI) for businesses striving to maximize their profits. BI, therefore, is a compelling alternative to GIS for network analysis, especially in a policy making environment. One critical issue though is the lack of proper geospatial capabilities in contemporary BI software.

At the heart of a BI project is an optimized data warehouse designed mainly using a star schema. The trick to unlock the power of BI for network analysis lies in successfully modelling a spatial topological infrastructure network using a star schema. In this study, we propose a star schema that can incorporate geometry data along with other network attributes to enable network analysis in BI. We demonstrate this star schema in action using a simple service vulnerability assessment on electricity networks.

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## Bio-inspired cost-effective access to big data

Lijuan Wang<sup>a</sup>  
Jun Shen<sup>a\*</sup>

**Abstract:** With the rapid proliferation of services and cloud computing, Big Data has become a significant phenomenon across many scientific disciplines and sectors of society, wherever huge amounts of data are generated and processed daily. End users will always seek higher-quality data access at lower prices. This demand poses challenges to service composers, service providers and data providers, who should maintain their service and data provision as cost-effectively as possible. This paper will apply bio-inspired approaches to achieving equilibrium among the otherwise competitive stakeholders. In addition to novel models of cost for Big Data provision, bio-inspired algorithms will be developed and validated for dynamic optimisation. Furthermore, the optimised algorithms will also be applied in the data-mining research on the Alpha Magnetic Spectrometer (AMS) experiment, which is aiming to find dark matter in the universe. This experiment typically receives 200G and generates 700G data daily.

**Key words:** Bio-inspired algorithm; Big data; Data-intensive service provision; Cloud computing

### I. Introduction

In recent years, the data generated by scientific activities, social networking, social media, as well as commercial applications has exponentially increased. This explosion of digital data and the dependence on data-intensive services are main characteristics of the IT tread in this decade. Big data is used to describe the exponential growth, availability and use of information, both structured and unstructured. Cloud computing has become a viable, mainstream solution for data processing, storage and distribution. It provides unlimited resources on demand.

Considering Big Data and the cloud together, we see a practical and economical way to deal with Big Data, which will accelerate the availability and acceptability of analysis of the data. To put Big Data to work, increasing numbers of companies are starting to use the cloud to publish Big Data as a data service. Many data services in the area of Big Data analytics have now become available.

The development of cloud computing and the delivery of Internet-scale data-intensive services have brought a number of challenges, such as the maintenance of quality of service

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<sup>a</sup> School of Information Systems and Technology, University of Wollongong, NSW, Australia

\*Corresponding author: Jun Shen [jshen@uow.edu.au](mailto:jshen@uow.edu.au)  
<http://dx.doi.org/10.14453/isngi2013.proc.42>

(QoS) as well as excellent opportunities for businesses to gain market share, and for scientific programs to save on cost and energy as well as on space for data management. Because the main motivation for moving to the cloud is to minimise cost (or maximise earnings), that is to say, for economic reasons, many studies attempt to find approaches to supporting cost-effective service provision from holistic perspectives.

In this paper, we address the cost-effective service provision issues and propose a bio-inspired model for data-intensive service provision. After giving the economic model, the problem and the three optimization phases of data-intensive service provision will be presented. Then, the advantages of applying bio-inspired algorithms to solve data-intensive service provision is presented, as well as some headway of our research in applying bio-inspired algorithms to tackling the problems. The case study is also described. Finally, we conclude this paper and propose future work.

## II. Problem statement

### • A. An economic model of data-intensive service provision

In general, data-intensive service composition will be supported cooperatively by data providers, service providers and service composers. Service providers and service composers become “service requesters” when they request data from data providers and services from other service providers. The various providers need a standardised way to regulate and price their resources<sup>1</sup>. The composite service should be constructed by achieving the Pareto optimum under the Nash equilibrium for the data-provider utility, the service-provider utility and the service-composer utility.

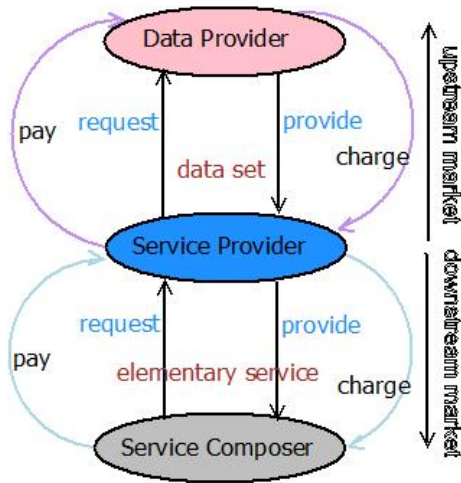


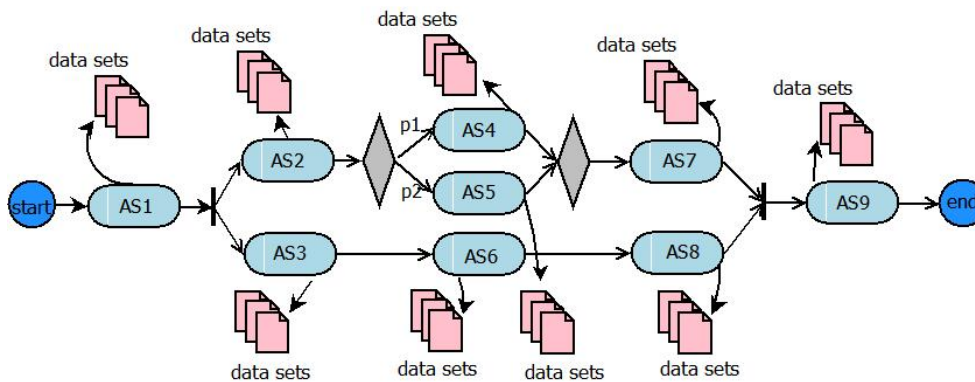
Figure 1. Service and data usage and the charging relationship.

An economic model of this service provision is assumed to be an accurate representation of the reality and to offer a suitable way to regulate the interaction among these providers. As shown in Fig. 1, in the downstream market, the service composer seeks optimal strategies to select elementary services provided by multiple service providers, who compete on the basis of price and quality of services. From the service composer’s point of view, it is important to be able to assess the value of the needed services and how much it wants to pay for them to satisfy

its users' requirements as well as maximising its own profit. From the service provider's perspective, it is important to be able to analyse its competitive position and improve its offers if it is to win contracts with the service composer. In the upstream market, the service provider requests the data from the data provider. The price and location of the data may affect the total cost and the price of services. Therefore the prices of service and data have a crucial impact on the service composer's and the service provider's profits.

- **B. Data-intensive service composition**

The data-intensive service composition problem is modelled as a directed graph, denoted as  $G = (V, E, D, \text{start}, \text{end})$ , where  $V = \{AS1, AS2, \dots, ASn\}$  and  $E$  represent the vertices and edges of the graph respectively,  $D = \{d1, d2, \dots, dz\}$  represents a set of  $z$  data servers. Fig. 2 gives an example of a directed graph for data-intensive service composition, in which data sets, as the inputs of services, are incorporated.



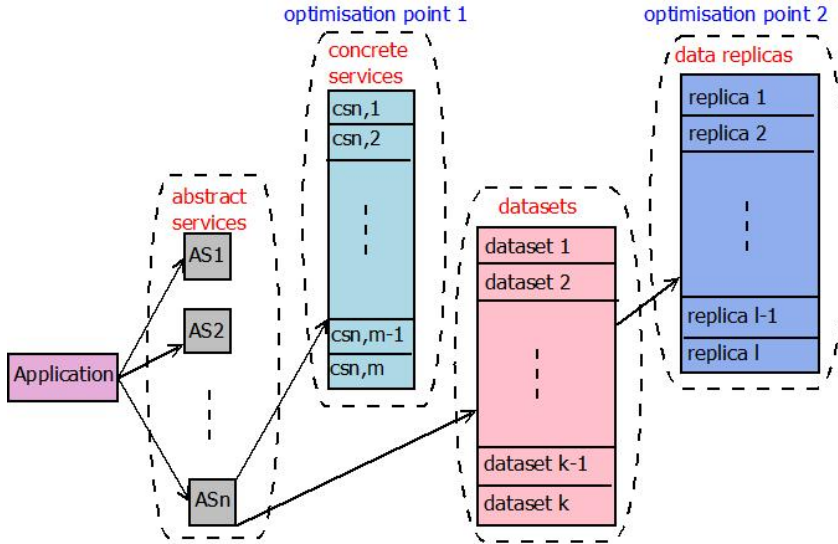
**Figure 2. Example of directed graph for data-intensive service composition.**

There are only two virtual vertices, the start vertex which has no predecessors, and the end vertex which has no successors. Each abstract service  $AS_i$  has its own service candidate set  $cs_i = \{cs_{i,1}, cs_{i,2}, \dots, cs_{i,m}\}$ ,  $i \in \{1, \dots, n\}$ , which includes all concrete services to execute  $AS_i$ . Each abstract service  $AS_i$  requires a set of  $k$  data sets, denoted by  $DT_i$ , that are distributed on a subset of  $D$ . A binary decision variable  $x_{i,j}$  is the constraint used to represent only one concrete service is selected to replace each abstract service during the process of service composition, where  $x_{i,j}$  is set to 1 if  $cs_{i,j}$  is selected to replace abstract service  $AS_i$  and 0 otherwise.

- **C. Optimizations in data-intensive service composition**

Data-intensive services raise new challenges for service composition. They need to access large numbers of datasets, which may be replicated at different data centres<sup>2,4</sup>. The economic cost of each data replica itself can never be overlooked because cloud computing is actually a model of business computing<sup>5</sup>. For one dataset, the access costs for a replica on one data center may be different from that for other data centres<sup>6</sup>. For this reason, it becomes very important to optimize data-replica selection<sup>5,7</sup>. In Ref. 8, it was pointed out that, although some research has considered the effect of data intensity on service composition<sup>9,10</sup>, the communication cost of mass data transfer and its effects on business processes with different structures was overlooked.

Therefore, the optimizations will be performed at two points during the lifetime of a data-intensive service composition, as shown in Figure. 3.



**Figure 3. Service and data selection in data-intensive service composition.**

The first optimisation phase occurs when the system uses a late-binding mechanism to choose concrete services. Because there may be many candidate services of similar functionality but different QoS that might be mapped to an abstract service, we need to select a set of candidate services. We refer to this phase as dynamic concrete-service selection. The second optimisation phase is dynamic data-replica selection. Because there may be multiple copies of each dataset, the services need to find the best available data replica. After these optimisations, a third optimisation phase is the dynamic optimisation and integration of candidate solutions, which globalises the two optimisations, achieved locally and will usually involve negotiations.

## II. Bio-inspired cost-effective to access big data

### • A. Bio-inspired algorithms to optimize data-intensive service provision

As explained above, it is important to develop mechanisms for selecting concrete services and data replicas to achieve a cost-effective solution for data-intensive service composition. The location of users, service composers, service providers and data providers will affect the total cost of service provision. Different providers will need to make decisions about how to price and pay for resources. Each of them wants to maximize its profit as well as retain its position in the marketplace. Dynamic service-price-setting models using non-standard pricing mechanisms, such as auctions and negotiations, are expected to appear for composing data-intensive services. Meanwhile, the QoS-based service-composition problem is regarded as a multi-objective or constrained combinatorial optimization problem. It is well known that the computational

complexity of service selection and negotiation is NP-hard. Data-intensive service provision faces challenges and constraints such as autonomy, scalability, adaptability and robustness.

Biological systems can satisfy these requirements optimally via evolution. They are autonomous entities and are often self-organized, without a central controller. Moreover, bio-inspired concepts and mechanisms have already been applied successfully to service-oriented systems by a few researchers, including some of our work in applying bio-inspired algorithms to tackling the problems related to data-intensive service provision<sup>11-18</sup>. Based on these existing studies, we are confident that bio-inspired algorithms present many advantages in dealing with data-intensive service-provision problems.

Bio-inspired optimization algorithms are proposed to solve the service-provision problem because of the simplicity of the algorithms and their rapid convergence to optimal or near-optimal solutions. Bio-inspired algorithms will also demonstrate their strengths in optimizing dynamic negotiations among service composers and service or data providers. Biological entities can learn from their environment. They can sense the surrounding conditions and adaptively invoke suitable behavior. We focus on service composition involving large amounts of data transfer, data placement and data storage, which make the cost issues for the whole composition more complex.

The optimization problem of service composition will be more critical when big data is present and involved in future services and cloud-based systems. To be able to allocate, aggregate<sup>13</sup>, duplicate and de-duplicate<sup>15</sup> unstructured data stored virtually everywhere, the configuration and management of data should be optimized, not only for reasons of performance and efficiency of data access, but also for lower cost and even the implicit energy and space savings in the maintenance of data storage.

- **B. Case study**

After construction of the system model and the design of the optimisation algorithm, the optimised algorithms will also be applied in the data-mining research on the Alpha Magnetic Spectrometer (AMS) experiment which uses cloud computing to process huge amounts of data. The AMS experiment is a large-scale international collaborative project, and the only large physics experiment on the International Space Station. The purpose of the AMS experiment is to study the universe and its origin by searching for antimatter and dark matter while performing precision measurements of cosmic rays composition and flux. The AMS lab is based at CERN in Switzerland. The key technology for accessing the data remotely collected from AMS relies on data services based on the cloud computing. This is actually supported by IBM Cloud Computing Center located at Southeast University in China. Typically, the center receives 200G bytes data from AMS and generates 700G bytes data after processing them, on each single day.

### **III. Conclusion**

In this paper, we present an economical model of data-intensive service provision and also give the problem and the three optimization phases during the lifetime of a data-intensive service composition. Our bio-inspired cost model uses all of the data-provision, service-provision and service-composition perspectives. In order to minimize the total cost of the data-intensive service

provision and to maximize each player's profit, we also need to design negotiation processes among different players. The design of the negotiation processes is currently under way.

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# Cost Benefit Analysis - Key Features and Future Directions

Spiller M<sup>a</sup>  
Deng Y<sup>b\*</sup>

**Abstract:** Cost Benefit Analysis (CBA) has played a critical role in public policy for more than 50 years. CBA goes beyond financial analysis which considers direct monetary costs and revenues. It enables policy makers to assess whether a policy initiative or project will provide a net community benefit, taking into account that the (limited) resources deployed in implementing the initiative or project have alternative productive uses. Correctly applied, CBA is a rigorous technique for evaluating projects competing for limited public sector resources. However, it does have its limitations and failings. To overcome the systemic failings, advanced CBA needs to be capable of tracking the long term and 'second round' benefits of major transport projects and better quantifying 'intangibles' that are fundamental to architectural and cultural building projects. There is a need for improved consistency across practitioners, through peer review and the publication of peer-endorsed methodologies for CBA.

**Key words:** Cost benefit analysis; Infrastructure project evaluation; Innovation; Future directions.

## I. What is cost benefit analysis?

An investment in a project effectively generates two types of benefits: those which are captured 'internally' (that is, by the investor as revenues) and those that accrue to the wider public, often referred to as 'positive externalities'.

For something like a major hotel or cultural development, the 'internal' benefits are equivalent to the revenues from overnight stays (in a hotel), expenditure on tickets or entrance fees and expenditure on merchandise from gift shops. The 'positive externalities' could include the growth in expenditure in the local economy generated by additional visitors attracted to the facility, enhanced amenity for pedestrians created by improved public domain around the building and, if the architecture is particularly special or striking, enhanced well-being and sense of pride amongst local residents. For a transport project like a major bridge crossing a river the positive externalities could include much faster travel times (because of the more direct route provided) and improved business formation and productivity as enterprises can better connect with each other and source the skills they need (also known as agglomeration economies).

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<sup>a</sup> SGS Economics and Planning, Melbourne, Australia,

<sup>b</sup> SGS Economics and Planning, Sydney, Australia

\*Corresponding author: Yuan Deng [yuandeng@sgsep.com.au](mailto:yuandeng@sgsep.com.au)  
<http://dx.doi.org/10.14453/isngi2013.proc.13>

Because many of the positive externalities are not traded – that is, there are no markets for them – and because they underpin the merits of and why we undertake public projects, there needs to be a means of evaluating them to make informed decisions about investment in a given project. Although there are a number of available evaluation techniques for evaluating public policies and investments, ‘cost benefit analysis’ (CBA) is the most widely accepted method amongst government and economists. CBA was first formally applied by government to evaluate water projects in the United States in 1936 and in the evaluation of transport projects in the UK around 1960<sup>1</sup>. This technique has also been used by the Ref. 2<sup>2</sup> to evaluate investments across the globe for over 40 years. It is now typically mandated by government processes relating to business case preparation, regulatory impact assessments and evaluation of strategic planning options.

The power of CBA as an economic evaluation method rests in two main features:

- Costs and benefits are, as far as possible, expressed in monetary terms and hence are directly comparable with one another;
- Costs and benefits are measured from the perspectives of all individuals in a community affected by a public policy or project, rather than any particular party, organisation or group.

Ultimately, the objective of CBA is to assist decision-making on the basis of the efficiency of resource use. ‘Efficiency’ here means the extent to which the application of labour, capital, land and environmental resources to a particular purpose contributes to the welfare of a community compared to the next best deployment of these resources. CBA evaluates the total costs and benefits of a policy proposal, plan and project to the community as a whole. It probes whether a policy initiative or project will provide a net community benefit, by comparing the opportunity costs of resources deployed in implementing the policy initiative or project with the benefits accruing to various members of the community. The benefits in CBA are generally measured by what individuals are willing to pay for them.

## **II. What are its key features?**

A CBA has a few defining features. First is the need to identify a ‘without’ project or ‘business as usual’ scenario, and one or multiple ‘with’ project scenarios. The CBA ultimately attempts to value the difference in outcomes between these scenarios (and therefore the impact of moving from business as usual to a different, project based future).

Secondly it is necessary to identify the range of economic, social and environment costs and benefits that might be expected in moving from the ‘without’ to ‘with’ project scenarios. It should be remembered that a business as usual or ‘without’ project scenario will also involve some changes and these need to be considered. It is the marginal change only that is evaluated.

Third is the quantification of costs and benefits. Accurate estimates of the monetary value of a number of costs and benefits will typically be available, drawn from capital outlays,

operational expenditure and revenue forecasts associated with similar projects. These are the ‘traded’ costs and benefits for which there is a market. For the non-traded costs and benefits – the negative and positive ‘externalities’ – it will be necessary to derive proxy monetary values for use in the analysis. Established techniques exist for this exercise for many costs and benefits – particularly those associated with travel or where the impacts will be translated into falling or rising property prices in the vicinity of the project.

Nevertheless, it is necessary to make assumptions to derive these ‘non-traded’ values, and quantification will be difficult if not impossible for many impacts. It is important to be explicit about assumptions and which costs and benefits can be quantified, and which cannot. Costs and benefits are allocated over a suitable project evaluation period, typically 25 years. Initial costs are usually associated with preparation and then construction. Revenues and benefits tend to begin to flow once the project is up and running. These costs and benefits need to be scheduled over time.

Finally, there is the generation of performance measurements using discounted cash flow techniques over the life of the project related costs and benefits. All values are discounted to the present using a ‘discount rate’. Essentially this makes an allowance for the fact that typically a dollar’s worth of benefit received today is valued more highly than a dollar’s worth of value delivered a few years later. Ref. 3<sup>3</sup> recommends a 7% discount rate with sensitivity tests of 4% and 10%. There are three main performance measures of project value in CBA:

- Net present value (NPV) - the sum of all costs and benefits expressed in present day values;
- Benefit-cost ratio (BCR) - the sum of benefits divided by the sum of costs expressed in present day values; and
- Internal rate of return (IRR) - the percentage return (of benefits) on the costs invested (technically, the discount rate which forces the NPV to equal zero).

The performance measures should be subject to ‘sensitivity tests’, which involves modifying the underlying assumptions to determine the variables that have a particular impact on the findings. A sound CBA also involves discussion or description of the costs and benefits that cannot be readily quantified. As noted, CBA focuses on net community benefit. In effect, a project is deemed worthy of investment if the beneficiaries from the project could compensate the losers and still remain in positive territory, regardless of whether they are actually called upon to effect such compensation. Nevertheless, decision makers are often interested in the equity of the spread of costs and benefit throughout societal and geographically defined groups. The question at this point is, are there particular parts of the state or country or particular economic groups that are disproportionately affected by the project in question?

### **III. Failings of Cost Benefit Analysis**

Correctly applied, CBA is a rigorous technique for evaluating projects competing for limited public sector resources. However, it has limitations and failings as recognised by Ref. 1<sup>1</sup>. In general, the failings of the technique fall into two categories - those that stem from a poor application or understanding of the approach, and those that are systemic or related to a lack of

good quality data. The former category of failings (those which stem from a poor application of the technique) includes the following.

#### **A. The Difficulty Of Quantifying Non-Traded Costs And Benefits**

No doubt this is problematic for cost benefit analysis with critics pointing to examples such as the quantification of the value of a human life, in the evaluation of road safety or other similar projects. This example definitely highlights an ethical weakness in the technique if applied without qualifications, but as the Australian Government's Cost Benefit Handbook points out, governments routinely imply a limit to the value of human life in not funding separated lanes on all major roads in Australia. Nevertheless, it is not possible to value all costs and benefits (and often the resources are not available to undertake the research to do so) so it is critical that an appropriate discussion and evaluation of non-quantifiable costs and benefits is included.

#### **B. False Accuracy**

Critics point to the fact that because there are assumptions involved, particularly in the quantification of 'intangibles' or non-traded costs and benefits, a false accuracy is attributed to the results of CBA. Again, it is important to recognise the limits of the analysis and describe the non-quantifiable costs and benefits fully, allowing for a judgment call by decision makers (which is ultimately a role for politicians). Another way to address the 'false accuracy' problem is to undertake the sensitivity testing mentioned earlier. There are inherent uncertainties in predicting the future but at least the range of potential outcomes can be considered if the inputs to the modelling are systematically varied. For example, a CBA which deals with major issues such as climate change would not be considered credible unless a range of scenarios and assumptions were tested.

#### **C. Equity Overlooked**

Because CBA measures overall (state or national) welfare or community wide impacts it is sometimes criticised for ignoring the way benefits and costs from projects fall unevenly (spatially or on different income groups). For example noise from a transport or airport project is likely to impact more harshly in an area where the costs of attenuation measures have to be met by lower income groups compared to the same costs having to be borne by wealthier people. The CBA would typically include this cost without regard to who bears it. However, as mentioned a robust CBA would be expected to make a commentary on the equity impacts. A robust CBA should not 'overreach'. Limitations and qualifications on findings are very appropriate. Nevertheless it is true that in the communication of results, or the expression of findings, these key dimensions – of the importance (or otherwise) of non-quantifiable costs and benefits, of the need to undertake sensitivity testing to identify impacts within a range and of overlooking equity impacts – are often overlooked. The focus will typically be on the key benchmark indicators without any qualifications. While the items mentioned above are typically failings in the application and reporting of CBA, there are more systemic weaknesses which do limit its application, particularly for major city shaping investments.

#### **D. Limited To 'First Round' Impacts**

CBA is evolving rapidly, with the range of impacts taken into account extending more broadly than direct user benefits and perhaps a limited range of obvious environmental externalities (such as emissions, safety, neighbourhood disruption and amenity). However, it is

conventional in cost benefit analysis to restrict measured impacts to the ‘first round effects’ of projects. While these may be subject to lags they have a direct ‘cause and effect’ link with the infrastructure item in question. Indirect and feedback effects are excluded, mainly for practical reasons; if second and subsequent round benefits are to be taken into account, so must costs, making the data gathering and analysis process very complex and open to challenge (because multiple judgements are required in identifying the effects). An example illustrating this weakness of CBA is the Sydney Opera House – which might be the cultural development or tourist facility, mentioned in the introduction to this article. This project would undoubtedly have fallen short against conventional CBA benchmarks. A sophisticated application of the technique may have identified some additional visitation and expenditure to Sydney generated by its iconic architectural status. However, it would have been very difficult to measure the reverberating and enduring benefits for the city from the sense of pride that it delivers to the city’s residents and importantly the strong imagery it provides for Sydney as a global city, and the additional investment this will have brought the city.

#### **E. Inappropriately Discounting The Future**

At the heart of CBA is the idea of discounting future costs and benefits. Typically, the discount rate chosen (usually 4-10%) means that any costs and benefits beyond 25 or 30 years are ‘discounted’ to a point where they have a negligible impact on the benchmark indicators. Conventional cost benefit analysis therefore tends to heavily ‘discount the future’. For major infrastructure projects which have the potential to re-shape the city for generations or for projects which have a major future environmental pay off, this is problematic.

A classic example to illustrate this CBA weakness is the Sydney Harbour Bridge – which might be the ‘major bridge crossing a river’ mentioned in the introduction. Like the Opera House it is unlikely a conventional cost benefit analysis would ever have generated the benchmarks to justify this project. The lead in period of planning, lost lives in construction and immense up-front investment might have been anticipated and would have been included in the CBA, with a trickle of benefits included over a 20 to 30 year project period. Clearly the technique conventionally applied is incapable of incorporating the long term benefits that the Harbour Bridge has delivered.

#### **F. Applying A Discount Rate To Increasingly Valued Future Benefits**

Similar to the above point, CBAs typically apply a common discount rate across all items. This ignores the fact that some benefits may actually increase in their ‘real’ value over time (e.g. vegetation with threatened bio-diversity values and particularly rare heritage items). A rigorous approach would apply lower discount rates to account for different intergenerational values.

### **IV. Conclusion: where to from here with CBA?**

CBA has played a critical role in public policy for more than 50 years now. In part, this is due to the dominance of market thinking in project and program formulation, that is, that any investment must provide a substantiated return in line with the value of the resources ‘given up’ by the community. This represents a significant shift away from former times, when major projects were (even more) influenced by political sponsorship and negotiation.

There have been some casualties in this shift. The relatively narrow focus of CBA on first round effects means that governments seem less capable of conceptualising and delivering major city shaping projects that are characterised by complex feedback effects and very long term payback periods. There is a need for CBA to evolve further, perhaps taking on more of the character of dynamic general equilibrium modelling, in terms of tracking long run effects, and linking this to land use outcomes.

Deepening the research and evidence base to better track and quantify ‘intangibles’ (pride, amenity impacts, potential ‘branding’ value) will be fundamental to iconic architectural and cultural building projects. The use of much lower or negative discount rates for items which will demonstrably increase their value in future is important for CBAs dealing with projects having cultural, heritage or environmental impacts.

There is also a need for improved consistency in application across practitioners. Governments have assisted by developing various guidelines with standard discount rates and default values for certain externalities. Nevertheless, different economists can come up with different findings for the same project, and these can be significant. Peer review has a role to play here, as does the publication of peer-endorsed methodologies for resource and benefit identification and valuation.

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# A Decision Framework for Investment in Supply Chain Driven Intermodal Systems

Hallock S <sup>a</sup>

**Abstract:** A research study identifying the role of ports, a forward timeframe of 30 years in servicing national supply chains is being undertaken. A paradigm shift to ‘water based’ freight solutions by barges and other forms of Short Sea Shipping (SSS) proposed in Hallock<sup>1,2</sup> as well as investigating stakeholder commitment to reducing their carbon footprint will be researched as part of this. Funding and better investment criteria will also be explored. The paper draws on European policy and governance frame works incorporating SSS as a component of the logistics response to sustainability. The green supply chain is now an important determinant of competitive advantage and is commercially acceptable.

**Key words:** Green Supply chain; Short-sea shipping; Infrastructure investment decisions; Ports; Policy frameworks.

## I. Introduction

Port and intermodal infrastructure decisions though impacting National Supply Chains, do not have an integrated framework within which they can be made. Such investments in Victoria and NSW will have a significant impact on urban form and create system interdependencies of surface transport but are logically evaluated locally with little consideration of national imperatives. Predictably States have assumed investment in surface transport to be, “more rail and road”, to service cargo movement generated by a port.

A paradigm shift to “water based” solutions by barges and other forms of Short Sea Shipping (SSS) was proposed in Hallock<sup>1,2</sup>. Such thinking would also be compatible with initiatives to promote sustainable transport and reduce the carbon footprint of freight. Greening the supply chain has been identified as an important component of the logistics response to sustainability. SSS is part of a policy framework in Europe and US and commercially acceptable. The green supply chain is now an important determinant of competitive advantage.

Major infrastructure decisions are best made using a 30 year strategic forward view, which will be used to identify and establish the role of major ports in servicing a National Supply Chain network. Exploration of; stakeholder’s commitment to reducing their carbon footprint and adopting sustainable transport practices such as SSS; development of innovative funding

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<sup>a</sup> Director- drh logistics International (pvt) ltd, Victoria 3150 and Colombo Sri Lanka  
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mechanisms alternate project evaluation methodology, and exploring whether commercial returns on investment are compatible with such outcomes will be explored.

## **I. Methodology**

A literature review has established several key concepts:

- Short Sea shipping is an environmentally sustainable mode of transport has a good fit with the greening of the supply chain.
- There is need for a paradigm shift in thinking in Australia in how sustainable transport occurs.
- Integrated thinking on investment in national logistics framework needs to occur.

A data collection phase not discussed in this paper will be based on interviews of key industry players including port operators, shipping lines, peak shipper bodies and will benchmark Australian adoption against International experience. The methodology will examine the use of Analytical Hierarchical Processing (AHP) within Multi-Criteria Decision Analysis (MCDA) frameworks and if possible Real options to arrive at a strategic decision based system usable by both state and Equity investors. The relevance to Federal research priorities as evidenced by the National Land Freight Strategy<sup>3</sup> will be examined. Prima facie this strategy provides less of a platform for the research themes of the Australian Transport Council which was replaced.

## **II. Literature Survey**

The survey of literature in the fields of SSS, *supply chains, greening the supply chain, the role of ports and intermodal infrastructure, sustainable transport and investment in enabling infrastructure* shows that there is a case to further explore these areas in the Australian context. No work has been done at an academic or industry level to explore opportunities or address all of the questions raised in a manner that attempts to integrate these streams of thought. A survey of literature to date suggests some of the themes are well supported as evidence presented below; on the other hand some themes require a more detailed survey of the literature-e.g. hubs in relation to Port –Supply chain interfaces and Port-Airport interfaces.

## **III. Short Sea Shipping**

The benefits of using Short Sea Shipping (SSS) as an alternate or complement to, road and rail modes, for short haul freight of future cargo flows within Melbourne's east-west-east corridor, was canvassed in Hallock and Wilson (op.cit.). A subsequent paper (Hallock 2010) developed two aspects of value capture and competitive advantage within the supply chain (SC) strengthening the case for integrating SSS into the SC<sup>2</sup>.

The implication of Hallock et al is to provide a framework of exploring this theme. A detailed discussion on the variants of a definition for SSS is provided in Hallock et al<sup>1</sup> and Medda and Trujillo<sup>4</sup>. In this paper we adopt Stopford's definition of short sea shipping (SSS) as "maritime transport within a region serving port to port feeder traffic in competition with land transport"



cited by Musso and Marchese<sup>5</sup> in their discussion on a definition for SSS. Medda and Trujillo (op.cit) contribute something new to the discussion on definitions for SSS when they identify the intermodal importance of SSS, as both a complement to road or rail as well as being a competitor when the potential exists to provide a point to point alternative to land transport<sup>5,4</sup>.

#### **IV. Alternatives to building infrastructure**

Federal and State research priorities around co-operative research, integrated research and action on environmental impacts as well as interdependencies with communities and stakeholders when reviewing long term land use for port cities will be examined.

#### **V. Value Capture in the supply chain**

Supply Chain Management (SCM) definitions use the concepts of “upstream and downstream” management of relationships, the delivery of value and the integration of suppliers (upstream) with customers (downstream), Christopher<sup>6</sup>, Mentzer et.al<sup>7</sup>. One definition of SCM is “a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer” Mentzer et.al<sup>8</sup>. A preferred definition, used in this paper, which incorporates the concepts of customer value and least cost, is SCM is the “management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole”<sup>6</sup>.

However recent thinking proposes that the supply chain is only part of the overall value chain and in fact requires the introduction of a demand chain to be a meaningful concept<sup>9</sup>. They go on to propose a model in which the cost efficiency and leanness of the SCM approach is supplemented by understanding customer and stakeholder expectations via demand chain processes. In their model of the value chain, supply chain decisions require the identification of a value proposition. This needs prior analysis of market attractivity, opportunity and organisational structure and resourcing. It is only then that the SCM decisions of value production and co-ordination can make sense. The advantage of the approach of Walters et al (op cit.) is that it emphasises value capture and value creation<sup>9</sup>. The application of the concept of value capture by integrating SSS into the SC can be explored further.

Value capture in global and domestic supply chains has hitherto focussed on efficiency e.g. techniques to compress lead times, reduce costs and improve customer service and recently lean concepts Levy<sup>10</sup>, Womack and Jones<sup>11</sup>. Value capture and value creation in a supply chain which relies on collaboration can be better understood from the point of view of Martinez<sup>12</sup> who proposes two aspects of value viz. internal focus on the creation of shareholder-wealth and the second external focus being from the customer’s view and being satisfaction driven.

Value migration was identified by Slywotzky<sup>13</sup> to be a phenomenon where value in an industry shifts over time and new business landscapes emerge; consequently outmoded business models give way to ‘new ones better able to satisfy customers’<sup>13</sup>. Robinson<sup>14</sup> takes the view that “pervasive value migration has created new value pools in port –oriented handling systems”<sup>14</sup>. For an excellent recent discussion of the concept relating to the pharmaceutical industry see

Walters and Rainbird<sup>15</sup>. Value capture in these circumstances enables strategic positioning to ensure long term strategic advantage.

## **VI. Ports and intermodal infrastructure**

A key change to the role of ports today is that ports are now takers not makers<sup>16</sup>. This hypothesis is supported in the literature<sup>17</sup> but will be tested in data collection.

## **VII. Value capture in the supply chain through SSS**

In Hallock, value capture in the SC relating to port/terminal situations was explored<sup>2</sup>. The potential for value capture in the SC through incorporating SSS into the SC via the terminalisation model was specifically discussed in the paper.

The potential to capture value by integrating SSS into the SC thereby leading to competitive advantage for users interested in sustainable supply chains was the second theme explored. Examples were provided of recent corporate interest in greening the SC and the author argues that this is not only important from the enterprise's viewpoint but also a path along which logistics should evolve to maintain its relevance in the future.

The evidence that short sea shipping has a role in value capture in strategic supply chain decisions because of environment and sustainability drivers and concerns is presented in detail. What needs to be noted here is that large retailers such as Wal-Mart have already required a demonstration of environmental stewardship on the part of their suppliers (including a baselining of Green-house Gas (GHG) emission per unit product). The implications for the SC in choosing low emission transport is immediately obvious. SSS offers a competitive advantage within the SC because it:

- Enables sustainability objectives to be met by users<sup>19</sup>.
- Minimises economic and environmental disbenefits<sup>27</sup>
- Allows unlocking of value by using a different operational paradigm<sup>17</sup>.

Examining each of these, there is evidence that concern with future impacts of present actions in environmental and sustainability areas is now informing the strategic SC and logistics choices made by commercial operators and policy choices of governments. The forwarder CONTARGO in the European North Continental Port range offers barges on both short routes of 50 km and longer routes with a matched value proposition to cargo needs. Three scenarios are offered: barge combination, truck only, rail combination, with CO2 emissions offsets provided for each scenario.<sup>18,19</sup> An example of government policy is the; European Commission's Motorways of the Sea concept which stems from the Trans European Transport Networks and Marco Polo program. Marco Polo is the European Union's funding programme for projects which shift freight transport from the road to sea, rail and inland waterways. This means fewer trucks on the road and thus less congestion, less pollution, and more reliable and efficient transport of goods. For instance, "a motorway of the sea route could be developed along the Atlantic coast to provide a sea-lane running parallel to motorways"<sup>20</sup>.

Golicic, Boerstler and Elram<sup>21</sup> observe that there are benefits to companies that integrate sustainability into their SC. They also note that freight transportation has moved from being of negligible consideration in company strategy to something monitored as a key part of SC sustainability practices, by both investors and customers. Golicic et.al surveyed 44 Fortune 500 companies and identified 22 that were trying to significantly address greenhouse gas emissions from freight transport in the supply chain .The 22 used a mixture of technological and operational tactics to achieve their goals. Eleven companies including Dell, HP, Estee Lauder making strategic choices on mode shift; thirteen companies including Walmart and FedEx used tactics which required a change to their fleet practices, e.g. through using alternate vehicle types and fuels, wider truck tyres etc.

### VIII. Reducing environmental impacts

The certainty that mode shift to SSS will result in economic and an environmental benefit has been extensively discussed in Hallock<sup>1</sup> and elsewhere. The pollution mitigation potential of SSS is recognised by numerous authorities – Perakis<sup>22</sup>, Marlow<sup>23</sup> and the ECT via its Marco Polo Program (ECT 2005)<sup>22,23</sup>. In EEC<sup>27</sup> data is provided showing the relative greenhouse gas (GHG) emissions by pollutant by mode<sup>24</sup>. BTRE<sup>25</sup> notes the social costs of congestion \$6.1bn for Melbourne by 2020 refers to estimated aggregate costs of delay, trip variability, vehicle operating expenses and motor vehicle emissions—associated with traffic congestion—being above the economic optimum level for the relevant network<sup>24</sup>. These costs are not “internalised” or paid for.

SSS is comparatively less polluting than road or rail. Australia has a national target of cutting greenhouse gas (GHG) emissions to 108 per cent of the levels they were in 1990<sup>26</sup>.

**Table 1. Evidence from the EEC, Green House Gas emissions from transport by Tonnes Mn’s.**

	Air Total Dom+Intl	Air Dom	Air Intl	Road	Rail	Shipping Total Coastal +Intl	Shipping -coastal	Shipping -Intl	Other	Total Trpt	Total Emissions
EU 27 states	155.4	25.6	129.8	902	7.8	194.6	23.4	171.3	10.1	1269.9	4558.7

Source EEC<sup>27</sup>

The BTRE have published the following for Australia:

**Table 2. Gigagrams of CO2 equivalent.**

	Cars	Road freight	Air	Rail	Coastal shipping	other	Total	
2000	40696	20762	4996	3518	1505	1980	73,456	
2020	50110	31874	11922	4848	1359	2292	102,406	

**Table 3. Composition of non CO2 non electric modes 2020 in Gigagrams.**

	NO <sub>x</sub>	CH <sub>4</sub>	NM VOC	CO	N <sub>2</sub> O
Rail	2623	64.4	0.23	21.8	0.08
Coastal shipping	28.6	0.07	1.16	2.94	0.04

Source Tables 2 and 3, BTRE op.cit -107 p 231 & 213 <sup>25</sup>.

## IX. Innovation

Unlocking value in a supply chain, of which SSS is an element also requires a change in the operational paradigm, in this case via the terminalisation model proposed by Rodrigue and Notteboom being extended to cover supply chains. Rodrigue and Notteboom have analysed the growing importance of two phenomena, gateway constraints and dwell times within the supply chain<sup>17</sup>.

The phenomena have been known to shipping practitioners but have only recently been considered by academics. The terminalisation model advocates the use of dwell times and a strategically widened role for terminal operators as a way value can be captured primarily by providing benefits in time and cost. The authors introduce the concept of modal separation of space and time, i.e. an opportunity for trading off time utility vs. space utility, as a means of unlocking value. The focus on buffer derived terminalisation is innovative. This is where there is an expectation that the warehouse becomes the buffer rather than more traditionally the distribution centre (DC). In essence it is an inventory in transit strategy which uses “inventory at terminal” to reduce warehousing cost and thereby total distribution cost.

It can succeed where DC/warehousing are costly and where shipping lines are chasing cargo. “Inventory in transit” was encountered by the author, when managing break bulk shipping (which did not always possess the clock work efficiency of container schedules) in trades having global supply chains. US and European consignees of some primary commodities and semi-processed agricultural produce preferred the slower transit time because it enabled them to use the vessel as a floating warehouse which phenomenon was recorded in Hallock<sup>28</sup>. Since SSS is an activity potentially replacing landside transfers the terminalisation of the supply chain can be extended to incorporate SSS. By doing so it facilitates value capture cost efficiency leading to creation of shareholder wealth on the one hand and customer satisfaction to those who want a green supply chain.

The research will also examine the concept of a Global Logistics Region developed by O'Connor<sup>29</sup>. The application of this concept and identifying the pre requisites of large extended regions and the breadth of freight activity is innovative. It has not been applied to Australia.

## X. Decision criteria

Decisions entailing uncertainty in strategic choices are not well handled by current evaluation techniques using variations of Benefit Cost Analysis. Although the use of structured “Gateway” processes by the State and Federal treasuries has helped, uncertainty has not been dealt with satisfactorily. The use of real options as done by Telstra (2003-2013) in the case of evaluating

technology with variable outcomes combined with multiple criteria analysis tools like Analytical Hierarchy Process and are other multi-dimensional evaluation techniques that can also be utilized<sup>30</sup>. For projects over \$750 M a critical examination of Wider Economic Benefits (WEBS) is analysed with a view to establishing whether or not this technique offers more than the use of CGE modelling. These alternatives are considered as providing an integrating decision framework for the choices in the areas under discussion.

## XI. Recommendation

The themes introduced in this paper are particularly relevant for the renewed discussion on funding of national infrastructure. They will be initially explored as a part of a doctoral dissertation and a decision model proposed for use in Australia.

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# **Incorporating time-series into an interindustry analysis to model the regional economic structure: a case study of the Illawarra**

Ashkan Masouman<sup>a\*</sup>  
Charles Harvie<sup>b</sup>

**Abstract:** Since the pioneering work of Glickman on embedding an input-output (IO) module into an econometric framework,<sup>1</sup> there has been a plethora of studies on combining an IO analysis with an econometric model in the literature. The popularity of the combined framework is due to its superior performance in economic forecasting and higher accuracy in impact analysis. There are a number of approaches through which an IO model is combined with an econometric model. This paper examines three approaches to combine IO analysis with econometric modelling, namely embedded, coupled, and linked. All three approaches are applied to the Illawarra economy in a series of ex-post forecasting experiments. Each approach is applied to a hypothetical scenario of sectoral reallocation of government expenditure, to investigate certain key sectors that provide more jobs per dollar of expenditure relative to the other sectors. The comparative forecasting performance and impact analysis accuracy of each approach is examined.

**Key words:** Input-output analysis; Econometric modelling; Regional analysis, Integrated framework.

## **I. Introduction**

One of the continuing attributes of regional science since its inception some 60 years ago has been on the development of tools for policy analysis. A significant emphasis has been placed on regional socioeconomic models, which covers the topic of regional analysis. The objective of this paper is to highlight the major contributions in the field of regional analysis. This paper focuses on one the most recent modelling developments, the integration of regional IO modelling with regional econometric modelling. In the past three decades, integrated models have been investigated by a number of economists to gain the benefits of both intersectoral details of IO modelling and dynamics of econometric modelling.<sup>2-10</sup> A thorough analysis of the studies in the literature reveals that there is an emerging consensus on the motivations for implementing integrated models into regional planning. It is a common credence among integrated modellers

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Northfields Ave, Wollongong NSW 2522, Australia

<sup>b</sup> School of Accounting, Economics & Finance, University of Wollongong, Northfields Ave, Wollongong NSW 2522, Australia

\*Corresponding author: Ashkan Masouman ashkan@uow.edu.au  
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that the traditional tools for regional analysis are inadequate to deal with the complexity of the issues that are of interest to regional analysts.<sup>3,11</sup>

To analyse the structure of a regional economy and to examine the potential impacts of policies on the future economy of a region, a regional analyst often applies two key methods (Other operational methods of regional analysis are computable general equilibrium (CGE), economic base analysis, shift-share analysis, linear programming, and cost-benefit analysis). The first method is IO modelling, through which the interactions between economic sectors are examined and the impacts of exogenous shocks on the economy are determined.<sup>10,12</sup> The multipliers in IO modelling enable analysts to calculate the direct and indirect effects of any shifts among various economic sectors and to trace the impacts of intersectoral transactions within an economy. The other method is econometric modelling, through which the growth rate of each sector is forecasted and the effects of a policy on high growth rate industries are evaluated. Nonetheless, each model applied alone ensue some drawbacks. For instance, IO models lack the dynamics of econometric models whilst on the other hand econometric models do not provide a detailed snapshot of intersectoral interactions among economic sectors of a region.<sup>9,13, 14, 15</sup> Given the two methods, applied alone in analysis, the question is if the results of evaluating the potential effects of a policy such as adjustment of overall rate of inflation or adjustment of relative prices of household expenditure commodities are highly accurate? Considering the limitations of each method in isolation, a positive answer to this question is highly doubtful.

West and Jackson<sup>10</sup> argue that in the standalone IO modelling, an exogenous shock to the economy entails a reaction from final demand to intermediate and primary inputs. Nonetheless, if changes in tax levels impact government expenditure, there is no reaction from primary inputs to final demand. Therefore it is required to implement a dynamic structure to apply time series in order to capture exogenous shocks through time. This feature can be gained by merging an IO model with an econometric model to combine the good properties of both methods<sup>1</sup>.

An integrated EC-IO model combines the advantages of both types of modelling, which in turn leads to increased accuracy in forecasting and to improved capabilities in impact analysis for regional planning. A significant number of studies have focused on applying the integrated framework in several regions within the U.S.<sup>4,6,8,14,16</sup>

However, in the Australian context, except for West<sup>9,17</sup>, no studies have been found in the literature focusing on the integrated EC-IO model to conduct regional analysis. The lack of studies in the literature on regional analysis is especially noticeable on the Illawarra region, which is an important region within New South Wales economy. Due to the economic transitions, as a result of globalization, that have occurred in the Illawarra's economy, an integrated EC-IO analysis on the Illawarra could be a stepping stone to further research on other regions around the globe that are similarly in a transitional phase. This paper explores the potential arising through the application of integrated EC-IO modelling to the Illawarra, a region in transition, to analyse the intersectoral relatedness and forecast structural shifts in the economy. Three different approaches are applied to unite the IO analysis with the econometric model, namely, coupled, embedded and linked approaches.



## **II. The region**

Due to globalization and structural adjustments over the last five decades, regions have become paramount factors in development of national economies. A new global environment of floating exchange rates, financial deregulation and globalization of capital markets has taken place over the last half a century. Consequently, the developed nations have entered an increasingly intricate and competitive global economy and in turn, the impact of regional economies on national economies has become vital in forming the dichotomy between the successful and the unsuccessful national economies.<sup>18</sup> Since four decades ago nearly all member states of organization for economic co-operation and development (OECD) have witnessed major economic and social shifts. These structural shifts indicate the fast pace of technological advancement, importance of knowledge sectors, capital market deregulation, and increased overseas trades.<sup>19</sup> Old industrial regions such as the Illawarra and New Castle in Australia; Lille in France; Liverpool in the UK; and Cleveland, Detroit and Pittsburgh in the US have declined or witnessed structural economic shifts as a result of globalization.<sup>18</sup> Regions such as the Illawarra in Australia and Waterloo, Ontario in Canada have adopted global learning skills and cross training labour characteristics and they heavily rely on skilled labour to adapt to the impact of globalization.

The importance of choosing the Illawarra as a region in this research is reflected in two paths. Firstly the Illawarra regional economy plays a key role in the context of the Australian economy, which is discussed in the following paragraph. Secondly, what adds to the significance of this study in terms of its pertinence to the global context is the application of the methodology in this paper to regions outside Australia, that have the characteristics similar to those of the Illawarra's. The emphasis on the Illawarra economy has shifted from heavy industry, steel manufacturing and mining to knowledge sectors and technological advancement, being regarded as city of innovation. This research is applicable to regions with demographics and economy size commensurate with the Illawarra, regions that have adapted to structural shifts in the past five decades as a result of globalisation and increased level of competition, and regions that are in a transitional process of economy as a result of structural shifts.

The Illawarra has contributed considerable resources to the economy of Australia as it has been a leading steel and coal exporter. It boasts the largest plant for steel production in the southern hemisphere.<sup>20</sup> The Illawarra is nationally acclaimed for metal fabrication and engineering. It has been considered the centre of excellence in research and development<sup>20</sup>, playing an integral role in technological advancement. In addition, it is a globally renowned provider of tertiary education.<sup>20</sup> According to the Australian Bureau of Statistics<sup>21-23</sup>, the Illawarra statistical division has an unemployment ratio of 6.7%. With a population of 436,117 people this indicates that nearly 13,114 of the current labour force are unemployed. Since one of the main objectives of regional planning is to increase employment, gaining higher accuracy in regional economic analysis would be a stepping stone in addressing the unemployment issues.

## **III. Comparison of the estimation results**

For the first experiment, the two integration approaches, namely the coupled and the holistic embedded, are applied to a dynamic ex-post scenario for forecasting both total and sectoral

employment for the period of 2009-2010. The reason for exclusion of standalone IO and linked approach is that due the static nature of those two models, they are not made for forecasting. Each of the two approaches in this experiment is based on parameters estimated over the 1990-2009 sample period. The comparison is made on the basis of mean absolute percentage error (MAPE) for the predicted values of each variable over the last two years of the sample period.

The results of the forecast show that the holistic embedded approach performs better than the coupled approach in forecasting total employment. This is due to the even distribution of the estimated values across all sectors, which is the main property of the holistic embedded approach. As noted on Table 1, the MAPE of the holistic embedded approach is far less than that of the coupled and the number of sectors with the lowest MAPE is four times that that of the coupled.

In terms of sectoral employment forecast, the coupled approach clearly outperforms the holistic embedded. The MAPE for the coupled approach is half of that of the holistic embedded and the number of sectors with the lowest MAPE is twice that of the embedded. A likely justification for this is that in a more diversified economy it is critical to avail of intersectoral linkages in defining the employment demand equations. The coupled approach imposes an exhaustive set of intersectoral relations in each employment equation and an extensive series of final demand equations; it is more sector-specific in terms of forecasting.

**Table 1. Coupled versus embedded: MAPE for total and sectoral employment forecasts**

Mean absolute percentage errors for total employment forecasts 2009-2010		
Integration approach	Coupled	Holistic Embedded
Illawarra	5.423	0.167
Number of sectors with lowest MAPE	4	16
Mean absolute percentage errors for sectoral employment forecasts 2009-2010		
Integration approach	Coupled	Holistic Embedded
Illawarra	3.756	6.459
Number of sectors with lowest MAPE	18	9

The second experiment is a comparison of the impact analysis capabilities of the three integration approaches, namely coupled, holistic embedding and linked, together with the standalone IO analysis. In these experiments, the four different models are applied to estimate the employment impacts on six sectors, arising from a hypothetical increase of AU\$1 million in government expenditure on three sectors, namely retail, education, and health and social services. Table 2 shows the results of the impact analysis of the coupled approach with respect to employment multipliers that it generated during.

**Table 2. Employment multipliers from the coupled model**

Sector	Employment Multipliers							
	Initial	First Round	Indust Sup	Consumption	Total	Elasticity	Type I	Type II
Agric, Forestry, Fis	9.6742	1.3721	0.4308	1.3373	12.8145	0.4058	1.1864	1.3246
Mining	1.5739	0.5007	0.2371	1.069	3.3808	1.379	1.4688	2.1481
Food Mfg	2.1145	2.3745	0.7137	1.5627	6.7654	0.3369	2.4605	3.1996
Textiles and Clothin	4.3976	1.4545	0.5411	2.0068	8.3999	0.613	1.4538	1.9101
Wood, Paper and Prin	3.6445	1.1757	0.4678	1.9583	7.2464	0.1532	1.451	1.9883
Petroleum and Coal P	0.4606	0.3787	0.1686	0.3972	1.4051	0.4812	2.1882	3.0505
Chemical Products	1.1916	0.8764	0.4061	1.2986	3.7726	1.2891	2.0763	3.1661
Rubber and Plastic P	2.4064	0.7241	0.3522	1.6071	5.0899	0.4517	1.4473	2.1151
Non-Metallic Mineral	1.9205	0.9947	0.5302	1.7749	5.2202	0.2599	1.794	2.7182
Basic Metals and Met	0.6432	0.3779	0.2301	0.6537	1.9048	2.3119	1.9453	2.9616
Transport and Other	2.9011	0.5237	0.279	1.5524	5.2562	0.8057	1.2767	1.8118
Other Manufacturing	6.3864	0.5332	0.267	1.6479	8.8345	0.9176	1.1253	1.3833
Electricity, Gas, Wa	2.6122	0.7618	0.3605	1.55	5.2846	0.4201	1.4297	2.023
Construction	3.4061	1.4059	0.81	1.8938	7.5158	1.6092	1.6506	2.2066
Wholesale Trade	2.9997	1.1688	0.5568	2.2383	6.9636	0.5854	1.5752	2.3214
Retail Trade	9.6509	0.9977	0.4879	2.7701	13.9066	0.0907	1.1539	1.441
Repairs	6.5239	0.8949	0.4417	1.9993	9.8599	0.4316	1.2049	1.5113
Accom, Cafes and Res	7.3278	1.0057	0.5073	2.1093	10.9502	0.0214	1.2065	1.4943
Transport and Storg	4.0713	1.1596	0.4849	2.0872	7.8029	0.6714	1.4039	1.9166
Communication Servic	2.0874	1.1542	0.5429	1.4387	5.2232	0.4742	1.813	2.5022
Finance and Insuranc	1.8253	0.5512	0.2495	2.5001	5.1261	0.1024	1.4387	2.8084
Ownership of Dwellin	0	0.4211	0.2058	0.4296	1.0565	0.6269	0	0
Rental, Hiring and R	2.3494	1.1196	0.5551	2.0441	6.0681	0.8151	1.7128	2.5828
Prof, Scientific and	3.6418	1.4701	0.7373	2.6276	8.4767	0.7877	1.6061	2.3276
Administrative Servi	4.924	1.1682	0.5394	3.1917	9.8233	0.8078	1.3468	1.995
Government and Defen	6.2997	0.9367	0.4427	3.1898	10.8688	1.621	1.219	1.7253
<b>Education and Traini*</b>	<b>9.6676</b>	<b>0.5237</b>	<b>0.2162</b>	<b>3.9038</b>	<b>14.3112</b>	<b>0.9052</b>	<b>1.0765</b>	<b>1.4803</b>
<b>Health and Social Se**</b>	<b>11.429</b>	<b>0.3985</b>	<b>0.1679</b>	<b>3.7088</b>	<b>15.7042</b>	<b>0.8249</b>	<b>1.0496</b>	<b>1.3741</b>
Cultural and Recreat	4.812	1.2454	0.5716	2.1111	8.7401	0.5755	1.3776	1.8163
<b>Personal and Other S***</b>	<b>11.9724</b>	<b>0.8154</b>	<b>0.3702</b>	<b>3.0686</b>	<b>16.2266</b>	<b>0.207</b>	<b>1.099</b>	<b>1.3553</b>

The first set of findings in the aforementioned experiment pertains to the comparison of the different models. The total estimated impacts generated by IO in each scenario are below 100 thousands and the flow-on effects below 65 thousands. These results are in sharp contrast with the results estimated from the linked approach, with total estimated impacts above 150 thousands and the flow-on effects nearly 90 thousands in all three scenarios. The results of the linked are substantially different also from the other two integrated approaches. In fact the estimate size of the total and flow-on effects of the linked model is the largest of the four models.

A possible reason for relatively large overestimation from the linked approach is the implicit double counting occurrence in modelling the linked approach. This occurs as a result of using IO analysis to estimate disaggregate total impacts caused by the government expenditure increase that are then aggregated and implemented into the econometric modelling to estimate the dynamic adjustments of the increase. Also the use of the Leontief inverse will extend the impacts of final demand change across other disaggregate sectors in the IO analysis. Hence, the linked multiplier interaction is not isolated to certain sectors in which the original change was introduced.

The substantial difference in the estimate results is due to differences in the structure of the employment demand equations across the three approaches. In general, coupled approach specifies sectoral employment as a function of sectoral output and labour productivity. In contrast in the other two approaches, employment is specified in a method similar to regular econometric modelling. Accordingly, the estimate variance in the linked and holistic embedded approaches is more commensurate with the econometric modelling whilst this variance in the coupled approach is in accordance with the detailed sectoral disaggregation of the IO analysis while retaining the dynamics of the econometric model to a higher extent than the other two approaches.

The second set of findings pertains to the importance of the sector with respect to its direct and flow-on effects on employment. By virtue of the competitive advantage of coupled approach, as a result of its exhaustive estimation and its superior accuracy, the sectoral comparison is conducted analysing the results of the coupled approach. As noted on Table 1, the sector which has the highest total impact on sectoral employment is retail trade. A million dollar increase of government expenditure on this sector increases nearly 15 thousands total impacts on employment. Of this 15 thousands total impact, 2.8% is the increase on the retail trade sector itself, then the highest impact is on transport and storage, which is 1.9% increase and third highest impact is on professional and scientific sector with 1.6% increase impact. The second sector resulting the highest impact on other sectors is education sector, with more than 12.5 thousands total impact and third health and social services with slightly more than 12 thousands impacts.

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# A New Approach to Bridge Infrastructure Management

Maria Rashidi<sup>a\*</sup>

Peter Gibson<sup>b</sup>

Tin Kin Ho<sup>a</sup>

**Abstract:** The maintenance of bridges as a key element in transportation infrastructure has become a major concern due to increasing traffic volumes, deterioration of existing bridges and well-publicised bridge failures. The main goal of this study is to develop a requirement-driven decision support methodology for remediation of concrete bridges within acceptable limits of safety, serviceability and sustainability. The proposed model includes two phases: Phase one is focused on condition assessment and priority ranking of bridge projects which makes use of an integrated priority index addressing a variety of factors. Phase two includes a multi criteria decision making technique which is able to select the best remediation strategy at both project and network level. The modified Simple Multi Attribute Rating Technique (SMART) is used as a decision analysis tool that employs the eigenvector approach of the Analytical Hierarchy Process (AHP) for criteria weighting.

**Key words:** Bridge management; Decision Support System (DSS); Simple Multi Attribute Rating Technique (SMART); Analytical Hierarchy Process (AHP); Maintenance; Rehabilitation and Replacement (MR&R).

## I. Introduction

Bridges are often subjected to high loads, harsh environments, and accidental damage. Determining what level of repair is required to achieve the most economical lifespan from a bridge structure has been a source of dilemma for asset managers and owners for many years. There are approximately 2.5 million bridges on the global higher transportation network. A recent study on bridge inventory estimated that there are approximately 50,000 bridges in Australia and only approximately 18% were constructed after 1976. Due to changes and increases in traffic load, structural degradation, and design code, many of these bridges do not meet the current Australian standards<sup>1</sup>. In 2005, the US Federal Highway Agency (FHWA) stated that 28% of their bridges are rated deficiently. In Europe this figure varies by around 10%. Nevertheless, if we consider a rough average of 20% deficiency, almost 500,000 bridges require remediation and improvement<sup>2</sup>.

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, 2522, Australia

<sup>b</sup> School of Mechanical, Materials, Mechatronics, University of Wollongong, 2522, Australia

\*Corresponding author: Maria Rashidi [mrashidi@uow.edu.au](mailto:mrashidi@uow.edu.au)

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In accordance with the limited funding for bridge management, maintenance, rehabilitation and replacement (MR&R) strategies have to be prioritised. A conservative bridge assessment will result in unnecessary actions, such as costly bridge strengthening or repairs<sup>3</sup>. But on the other hand, any bridge maintenance negligence and delayed actions (or ignoring the cause of defects) may lead to heavy future costs or degraded assets.

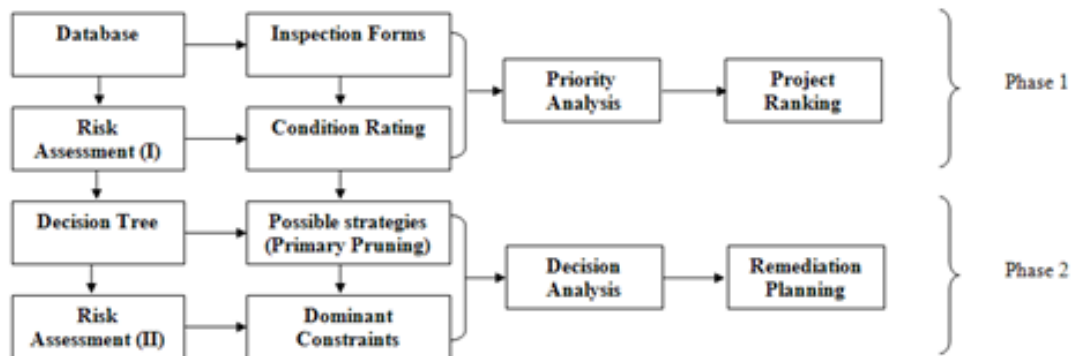


Figure 1. Conceptual Framework for Bridge Management<sup>4</sup>

## II. The Proposed Framework for Bridge Infrastructure Management

The system methodology presented in this paper deals with the development of a knowledge-based decision support model for bridge infrastructure management as a solution for the problems and limitations of the existing models. The proposed model is expected to be flexible and capable of handling multi-layer of data and dealing with multi-objective nature of the decision. The working model includes a procedure for condition assessment in order to prioritise bridges in a network for any necessary intervention and finally proposing a remediation strategy at both project level and network level. Classifying all the possible actions (including MR&R strategies and/or treatment options), finding the main constraints and finally employing a suitable decision analysis tool are the main components of the proposed system. Figure 1 shows the overall working framework including two main phases which will finally lead to two major outputs: 1) Project Ranking and 2) Remediation Planning.

Multi criteria nature of the decision making involves various parameters with different importance level. Weighting the engaged factors has been partially accomplished through expert judgements employing Analytical Hierarchy Process (AHP) as a strong tool designed for this purpose. Through the AHP, decision problems are decomposed into a hierarchical structure, and both qualitative and quantitative information can be used to derive ratio scales between the decision elements at each hierarchical level by means of pair wise comparisons. With comparative judgments, users are requested to set up a comparison matrix at each hierarchy by comparing pairs of criteria or sub-criteria. A scale of values ranging from 1 (indifference) to 9 (extreme preference) is used to express the users preference. Finally, in the synthesis of priority stage, each comparison matrix is then solved by an eigenvector method for determining the criteria importance<sup>5</sup>.



### III.

#### IV. Phase One: Project Ranking

The reliability of decisions to prioritise bridges for fund allocation is highly dependent upon the thoroughness of the condition assessment and diagnosis process<sup>4</sup>. Most of the existing approaches are commonly based on subjective structural condition assessment. Parameters such as functionality and client preferences may not be specifically addressed in them. As a result, one of the main objectives of this research was to propose an integrated index for the bridge rating, in a requirement driven context. The developing condition rating method described in this paper is an important step toward this aim and along with adding more holism and objectivity to the current methods. The analysis and quantification of Structural Efficiency (SE), Functional Efficiency (FE) and Client Impact Factor (CIF) are addressed in the proposed model.

The first step to evaluate structural efficiency is dividing the bridge into elements generally made of a similar material. The inspector estimates and records the quantities of the bridge element in each condition state independently. The total quantity must be measured in the correct units for the elements. The element condition index can be calculated as the current value divided by the initial value of the bridge element. To describe the overall condition status of structural elements, the Element Structural Condition Index (ESCI) is introduced as:

$$ESCI = \frac{\sum(qi \times ci)}{\sum qi} \quad (1)$$

- $qi$  is the quantity of elements reported in condition index  $ci$
- $ci$  is the condition of sub-element  $i$   $ci \in (1,2,3,4)$

According to Equation 1, the element condition index ranges from 1 to 4. In order to be in harmony with the existing evaluation, the quantities assigned for the relative evaluation of the involved parameters (achieved through expert judgements) have been limited to the same range (see Table 1).

Generally, the prevailing condition (rating) of the particular element may cause some inaccuracies in the overall structural assessment. For example, a minor component with worse condition may unreasonably raise the rating value of element under which the component is grouped. This problem has been resolved with the introduction of an element structural significance factor ( $Si$ ) which is not dependent on the prevailing condition of components (see Table 1). The higher numbers represent the superior importance of structurally critical members which have a great impact on the strength and safety of the structure and where failure of the member could lead to catastrophic collapse.

Different materials have different contributions to the structural efficiency of a bridge. For example reinforced concrete is more vulnerable than steel and the structural vulnerability of precast concrete is more than reinforced concrete. Therefore material factor should be considered in the structural assessment of bridge elements. Table 1 presents the vulnerability factor of common materials used in concrete bridges introduced as  $Mi$  which is obtained from the work of Valenzuela et al. (2010)<sup>6</sup> and validated by the judgements of structural engineers. Based on vulnerability of different materials it varies between 1 and 4<sup>7</sup>.

Bridge elements deteriorate over an extended period of time and the rate of deterioration is a function of various parameters. Apart from some pre-existing factors such as design and construction, there are several post existing causes involved in the structural efficiency of bridges. These include the environment where the structure is located in, the length of time the structure has been in service (Age), the function the structure is required to perform (Road Class) and the quality of inspection and monitoring. The impact of CF on the bridge structural efficiency can be evaluated through Equation 2. The weights of the involved parameters have been estimated using AHP and the associated ratings are defined based on the classifications presented in Table 1.<sup>7</sup>

$$CF = 0.411A + 0.120E + 0.107R + 0.362I \quad (2)$$

The overall Structural Efficiency index (SE) is a dimensionless relative parameter that integrates all the elements which influence structural effectiveness and is estimated as follows<sup>8</sup>:

$$SE = \frac{CF \sum (M_i \times S_i \times ESCI_i)}{16n} \quad (3)$$

The range of SE varies from 1 to 4. The priority for remedial action increases as the number increases (n represents the number of element types). The modern BMS considers the quality of service (functional efficiency) in addition to structural efficiency. Yannev (2007)<sup>9</sup> stated that “the functional life of bridges is less than the structural life,” e.g., 25 to 50 years (in high traffic growth), compared to 50 to 100 years (except disasters).

According to Rashidi and Lemass (2011)<sup>4</sup>, the bridge functional efficiency is dependent on the traffic volume that it can withstand, which is mainly related to the load bearing capacity of the bridge, existing number of lanes or the width of the deck, vertical clearance and the barriers. The drainage system, provisions for pedestrians and cyclists and any post design changes should also be carefully considered in the assessment process. Any deficiency associated with the above items can reduce the level of service and accelerate the deterioration process. For this reason, it is advantageous to consider the elimination of these deficiencies within the decision making process. Five main deficiencies that can seriously affect bridge safety and serviceability are: load bearing capacity, vertical clearance, width, barriers and the drainage system. The overall functional efficiency factor (FE) can be calculated using the ratings (See Table 1) and the weights as shown in the Equation 4.

$$FE = 0.7Lc + 0.1Vc + 0.1Wb + 0.05Bb + 0.05Ds \quad (4)$$

- Lc is the load bearing capacity
- Vc is the vertical clearance
- Wb is the width
- Bb is the barrier
- Ds is the drainage system

The nature of a bridge site and the extent of the bridge remediation treatment may cause decision makers to close bridge lanes or create alternative routes or bypasses to control the traffic flow. Excessive traffic delay times often result in negative feedback from both the road users and their political representatives. Client Impact Factor (CIF) helps build the social implications of remediation into the risk assessment process. It is a vast improvement on the

'do nothing' course of action. On the other hand, the bridge's importance for economic activity can accelerate the decision making process toward 'replacement' or 'rehabilitation'<sup>10</sup>. This factor can be ranked based on the level of bridge criticality in terms of socio-economic, political and historical considerations as shown in Table 1. The key decision maker or bridge maintenance planner will be responsible to rate this parameter based on their understanding of client preferences. Finally the Priority Index (PI) integrates all the above mentioned factors that will influence decision making through the following equation:

$$PI = 0.6SE + 0.2FE + 0.2CIF \quad (5)$$

Using PI enables bridge/funding agencies to make decisions and set objectives backed up by strong logic. By using this technique all bridges are sorted in descending order starting

**Table 1. Ratings of All the Contributed Parameters in Condition Rating and Prioritisation**

Ratings	STRUCTURAL EFFICIENCY (SE)						FUNCTIONAL EFFICIENCY (FE)					CLIENT IMPACT FACTOR (CIF)
	Structural Significance Factor (Si)	Material Vulnerability Factor (Mi)	Causal Factors (CF)									
			Age (A)	Environmental Aggressive Factor (E)	Road Class (R)	Inspection quality (I)	Load Bearing Capacity (Lc)	Vertical Clearance (Vc)	Width (Wb)	Bridge Barrier (Bb)	Drainage System (Ds)	
1	Barriers, Footway, Kerbs, Joints	Steel	Recently Built	Low	Minor	Very High	L≥1	V≤5	Wb≤5	Bb≤5	Very Good	Low
2	Foundation, Abutment, Wingwalls	Reinforced Concrete	New	Medium	Local Access	High	0.9≤L<1.0	5<V≤12	5<Wb≤12	5<Bb≤12	Good	Medium
3	Deck, Bearings	Precast Concrete	Old	High	Collectors	Medium	0.7≤L<0.9	12<V≤20	12<Wb≤20	12<Bb≤20	Fair	High
4	Beams, Headstocks, Piers	Prestressed Concrete	Very Old	Very High	Arterials	Low	L<0.7	V≥20	Wb≥20	Bb≥20	Poor	Very High

with the bridge with the highest ranking index, the required actions are carried out until the allocated funds are exhausted.

## V. Phase Two: Remediation Planning

Sound decision making requires including multiple and conflicting criteria in the process. Five major categories of criteria including safety, functionality, sustainability, environment and legal/political constraints have been identified through level two of risk assessment. Different decision analysis tools have also been analysed and the modified Simple Multi Attribute Ranking Method (SMART) was selected as the main frame work for strategy selection.

Through the SMART process, firstly, the problem under consideration is mapped into a hierarchy, including at least three main levels: goal, criteria and alternatives. The decision sub-criteria might be general and they may therefore require to be broken down into more specific sub-criteria introduced as attributes in an extra level of hierarchy. Each criterion has a weight indicating its importance and reflecting the organizational policy. These weights are defined by the decision makers employing the pair wise comparison approach embedded in the AHP and will vary for different projects with different decision makers<sup>10</sup>.

The AHP has the major benefit of allowing the decision makers to carry out a consistency check for the developed judgment in regard to its relative importance among the decision making components. Therefore, the decision maker(s) can modify their judgments to improve the consistency and to supply more-informed judgments under consideration. The procedure is also able to provide flexibility in selecting the criteria to be used to evaluate the

rehabilitation strategies and even increasing or decreasing the numbers of levels (associated with the criteria) in the hierarchy.

## VI. Conclusion

The main scope of this research was to develop a decision support methodology for bridge remediation that would improve knowledge in the area of infrastructure management. Based on the achieved developments, this research made a number of contributions which will be beneficial to transportation agencies and infrastructure asset managers. The proposed model is able to add more objectivity to the existing systems through quantifying the major parameters and considering both the project and network aspects of the infrastructure management plan. The analysis of case studies and the feedback received from the experts confirms the applicability of the system.

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# Efficiency and equity analysis of toll pricing on Sydney Harbour Bridge with heterogeneous travellers

S. Wang <sup>a\*</sup>  
M. Dunbar <sup>b\*</sup>  
M. Harrison <sup>b</sup>

**Abstract:** Sydney Harbour Bridge is a key transport infrastructure that connects North Sydney and Sydney Central Business District (CBD). To alleviate the congestion on Sydney Harbour Bridge, NSW Roads and Maritime Services imposes a time of day tolling between \$2.5 and \$4 on the southbound traffic to Sydney CBD. This study develops mathematical models for formulating the toll pricing problem on Sydney Harbour Bridge considering that different travellers may have different value-of-times (VOTs). The models examine quantitatively the effect of different toll levels on the efficiency (in terms of the total generalized travel time and generalized travel cost of all travellers) and equity (in terms of the ratio of generalized travel cost among different traveller classes). The proposed models can serve as a useful decision-support tool for NSW Roads and Maritime Services.

**Key words:** Toll pricing; Traffic equilibrium; Heterogeneous value-of-time; Sydney Harbour Bridge; Optimization.

## I. Introduction

In view of the importance of the Sydney Harbour Bridge on transport efficiency in Sydney, this paper develops mathematical models for formulating the toll pricing problem on Sydney Harbour Bridge considering that different travellers may have different value-of-times (VOTs). The models examine quantitatively the effect of different toll levels on the efficiency and equity. The objective is to provide a useful decision-support tool for NSW Roads and Maritime Services.

## II. Toll pricing with homogeneous travellers

We assume that there are two roads from North Sydney to CBD of Sydney: one via Sydney Harbour Bridge (link *a*) and the other via other bridges (link *b*), see Figure 1. Link *b* is longer and has a larger capacity than link *a*. The link travel time functions are assumed to be of the Bureau of Public Roads (BPR) form:

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<sup>a</sup> Lecturer, Ph.D. School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, NSW 2522, Australia. Email: [wangshuaian@gmail.com](mailto:wangshuaian@gmail.com)

<sup>b</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, NSW 2522, Australia,

\*Corresponding Author: Michelle Dunbar [mdunbar@uow.edu.au](mailto:mdunbar@uow.edu.au)

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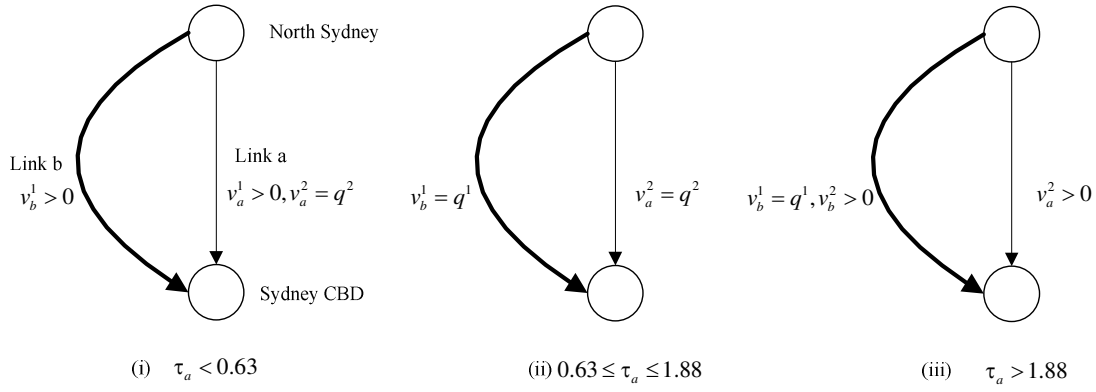
$$t_i(v_i) = t_i^0 \left[ 1 + \alpha_i \left( \frac{v_i}{C_i} \right)^{\beta_i} \right], i \in \{a, b\} \quad (1)$$

where  $t_i^0$  is the free-flow travel time (minutes),  $v_i$  (vph) is the traffic flow,  $C_i$  (vph) is the link flow capacity, and  $\alpha_i > 0$  and  $\beta_i > 1$  are two parameters.

We represent by  $q$  (vph) the travel demand from North Sydney to Sydney CBD, and we denote by  $v_a$  and  $v_b$  the flow on link  $a$  and  $b$ , respectively. The link flow must satisfy flow conservation equations. For simplicity, we define a set:

$$\Omega = \{(v_a, v_b) \mid v_a + v_b = q, v_a \geq 0, v_b \geq 0\} \quad (2)$$

containing all the possible link flow vector  $v := (v_a, v_b) \in \Omega$ .



**Figure 1. Transport flow with different tolls.**

#### A. User equilibrium, system optimum, and optimal toll pricing

Since each traveller aims to minimize her/his travel time, at the user equilibrium (UE), if no toll is imposed, the travel times on the two links are identical  $t_a(v_a) = t_b(v_b)$ . We assume that all travelers are homogeneous with value of time (VOT)  $\gamma$  (\$/min). If the government imposes toll on both links denoted by  $\tau := (\tau_a, \tau_b)$ , the equilibrium is:

$$\gamma t_a(v_a) + \tau_a = \gamma t_b(v_b) + \tau_b \quad (3)$$

We can compute the resulting link flow  $v_a$  and  $v_b$  denoted by  $v^{UE}$ .

At system optimum (SO), the total travel time of all road users is minimized, and the SO link flow is denoted by  $v^{SO}$ . The optimal SO toll denoted by  $\tau^*$  can be computed by the marginal social cost theory. Alternatively, the government may impose a non-zero toll on only one link by requiring that:

$$\tau_a = \tau_a^* - \min\{\tau_a^*, \tau_b^*\} \quad (4)$$

$$\tau_b = \tau_b^* - \min\{\tau_a^*, \tau_b^*\} \quad (5)$$

### B. An example using Sydney Harbour Bridge

We use the case of Sydney Harbour Bridge to demonstrate the above models. The free-flow travel time of Sydney Harbour Bridge is calculated as follows. It is 1.149 km long and we assume a free-flow travel speed of 80 km/h. Hence,  $t_a^0 = 0.86$  min. It has 8 traffic lanes controlled by Electronic Lane Changing System (ELCS). Therefore we assume that 6 lanes are used in the southbound direction during morning peak. We further assume that the capacity of one lane is 2000 vehicles/h. Consequently,  $C_a = 12,000$ . The coefficients  $\alpha_a = 0.15$  and  $\beta_a = 2$ . We assume that the length of link  $b$  is 5km, its free-flow travel speed is 80 km/h, and it has 20 lanes. Therefore,  $t_b^0 = 3.75$  and  $C_b = 40,000$ . The coefficients  $\alpha_b = 0.15$  and  $\beta_a = 4$ . We assume  $\beta_b > \beta_a$  because the traffic on Sydney Harbour Bridge is well controlled and regulated. We assume that the demand in the peak hour is 120,000 vph. The value of time  $\gamma = 0.5$  \$/min. The results are reported in Table 1, where the row “*Toll (\$4)*” means a toll of \$4 is charged on Sydney Harbour Bridge and the column “*TTT*” means the total travel time of all travelers as defined below:

$$TTT = v_a t_a(v_a) + v_b t_b(v_b) \quad (6)$$

When \$4 is charged (which is the actual toll charge during morning and evening peak hours on weekdays), the flow on Sydney Harbour Bridge is 45,050. To achieve the SO traffic flow, the optimal toll charge on Sydney Harbour Bridge should be \$0.36. The toll charge \$4 is apparently too high, and the resulting TTT is not only larger than that under SO, but also significantly larger than that without any intervention (UE).

**Table 1. Results with homogeneous travellers.**

	$v_a$	$v_b$	$t_a(v_a)$	$t_b(v_b)$	$\tau_a$	TTT
No toll (UE)	69,422	50,578	5.188	5.188	0	622,550
SO	66,480	53,520	4.829	5.553	0.36 <sup>i</sup>	618,219
Toll (\$4)	45,050	74,950	2.684	10.684	4	921,642

### III. Toll pricing with heterogeneous travelers

We examine heterogeneous travellers in this section. We consider  $M$  traveller classes, and the VOT of class  $m = 1, 2, \dots, M$  is denoted by  $\gamma^m$  (\$/min). The demand of class  $m$  is  $q^m$ . The number of travellers from class  $m$  on link  $i$  is denoted by  $v_i^m$ . For simplicity, we define a set:

$$\hat{\Omega} = \left\{ (v_a^m, v_b^m, m = 1, 2, \dots, M) \mid v_a^m + v_b^m = q^m, v_a^m \geq 0, v_b^m \geq 0, \forall m \right\} \quad (7)$$

containing all the possible link flow vector  $v := (v_a^m, v_b^m, m = 1, \dots, M) \in \hat{\Omega}$ .

<sup>i</sup> This is the optimal  $\tau_a$  to achieve SO with  $\tau_b = 0$ .

### C. User equilibrium, system optimum, and optimal toll pricing

With heterogeneous travellers, there are two types of SO: SO in cost units and SO in time units. The SO model in cost units can be formulated as:

$$\min \sum_{m=1}^M \gamma^m [v_a^m t_a(v_a) + v_b^m t_b(v_b)] \quad (8)$$

According to Ref. 1, the optimal toll can be computed.

### D. An example using Sydney Harbour Bridge

We look at the Sydney Harbour Bridge example again, and assume two classes:  $\gamma^1 = 0.25$ ,  $\gamma^2 = 0.75$ ,  $q^1 = 60,000$  and  $q^2 = 60,000$ . Therefore the total demand and the average VOT are the same as sub-section II.B.

The results are reported in Table 2, where the column “*Toll (\$4)*” means a toll of \$4 is charged on Sydney Harbour Bridge. The column “*TTT*” means the total travel time of all travellers defined by Eq. (6). The column “*TTC*” means the total travel cost of all travellers defined below:

$$TTC = \sum_{m=1}^M \gamma^m [v_a^m t_a(v_a) + v_b^m t_b(v_b)] \quad (9)$$

We can see that to minimize total travel cost, a toll of \$1.92 should be imposed on Sydney Harbour Bridge, and only travellers in class 2 use Sydney Harbour Bridge. Both travellers in class 1 and class 2 use other bridges, and hence their generalized travel time is the same, and their generalized travel cost is proportional to their VOTs. If we minimize the total travel time, then slightly fewer people use Sydney Harbour Bridge than the case of no toll (UE). To this end, a toll of \$0.18 is imposed and therefore all travellers in class 2 use Sydney Harbour Bridge. Travellers in class 1 use both links. Since travellers in class 1 and class 2 have the same travel time and pay the same toll on Sydney Harbour Bridge, the ratio of the generalized travel cost between class 2 and class 1 is reduced from 3 to 2.740.

When a toll of \$4 is imposed on Sydney Harbour Bridge, then only travellers in class 2 use it. This case is similar to the case of Cost SO and since both travellers in class 1 and class 2 use the untolled link, their generalized travel time is identical.

**Table 2. Results with heterogeneous travellers.**

	No toll (UE)	Cost SO	Time SO	Toll (\$4)
$v_a^1$	34,711	0	6,480	0
$v_a^2$	34,711	59,819	60,000	51,531
$v_b^1$	25,289	60,000	53,520	60,000
$v_b^2$	25,289	181	0	8,469
$t_a(v_a)$	5.188	4.074	4.829	3.245
$t_b(v_b)$	5.188	6.632	5.553	8.579



$\tau_a$	0	1.92 <sup>j</sup>	0.18 <sup>k</sup>	4
Generalized time for class 1	5.188	6.632	5.553	8.579
Generalized time for class 2	5.188	6.632	5.070	8.579
Generalized cost for class 1	1.297	1.658	1.388	2.145
Generalized cost for class 2	3.891	4.974	3.803	6.434
Ratio of cost of class 2 over cost of class 1	3.000	3.000	2.740	3.000
TTT	662,550	642,824	618,219	754,636
TTC	311,276	283,153	308,421	308,607

### E. Impact analysis of different toll levels

We further analyse the flow pattern under different toll levels, and the results are shown in Figure 1. When  $\tau_a < 0.63$ , travelers in class 1 and all travellers in class 2 use Sydney Harbour Bridge and experience the same travel time and toll; some travellers in class 1 use other bridges. Therefore, the ratio of the generalized travel cost of class 2 and class 1 is between 3 and 2.24 (less than the ratio of their VOTs). When  $0.63 \leq \tau_a \leq 1.88$ , all travellers in class 2 use Sydney Harbour Bridge and all travellers in class 1 use other bridges. The ratio of the generalized travel cost is between 2.24 and 3.00. When  $\tau_a > 1.88$ , some travellers in class 2 use Sydney Harbour Bridge; all travellers in class 1 and the other travellers in class 2 use other bridges. Therefore, on link  $b$ , the two classes of travellers experience the same travel time and zero tolls. The ratio of the generalized travel cost is 3.00.

## IV. Conclusions

This paper has developed mathematical models for formulating the toll pricing problem on Sydney Harbour Bridge considering that different travellers may have different value-of-times. The models examine quantitatively the effect of different toll levels on the efficiency and equity. The proposed models can serve as a useful decision-support tool for NSW Roads and Maritime Services.

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<sup>j</sup> This is the optimal  $\tau_a$  to achieve Cost SO with  $\tau_b = 0$ .

<sup>k</sup> This is the optimal  $\tau_a$  to achieve Cost SO with  $\tau_b = 0$ .

# Strategic Appraisal of Interdependent Infrastructure Provision: A Case Study From the Thames Hub

Kate Young<sup>a</sup>  
Jim Hall<sup>a</sup>

**Abstract:** Evaluation of potential infrastructure projects varies from straightforward financial assessment, to explicit methods requiring multi-criteria valuation and uncertainty analysis. All, however, are siloed to their own sector and in many cases the stand-alone project under consideration, ignoring the growing interdependence between the sectors. Here we develop a long-term multi-sector, multi-attribute decision analysis, demonstrated through a case study on the Thames Hub proposal. Uncertainty is assessed through sensitivity analysis, provisioning time-dependency analysis and an adapted real options analysis, to produce bounded valuation of decision pathways. Further consideration of spatial feedbacks is then reviewed through a land-use transport model. The results are brought together to demonstrate a strategic, integrated infrastructure assessment methodology, focused on delivering long-term resilience despite uncertainty.

**Key words:** Infrastructure systems; Interdependency; Flexibility; Multi-criteria analysis; Decision support; Real options

## I. Introduction

The five lifeline infrastructures (communications, energy, transport, water and waste) have vast impacts on the populous' wellbeing, the environment and the financial welfare of the country. Yet, while it is acknowledged these infrastructures function as a system of systems, appraisal of new infrastructure provision is made at the sector, or individual asset level. This reduction of the system complexity significantly limits the validity of results<sup>1</sup>, (i) ignoring macro-scale impacts, such as economic growth, which only manifest where systems complement each other<sup>2,3</sup>; (ii) concealing resource constraints, where decisions make other options impossible to realise or invalidate the business case behind them; and (iii) ignoring direct (and indirect) demand on other sectors.

Errors are further extrapolated due to the long term nature and time dependency of infrastructure investments. Infrastructure benefits are highly dependent on the performance of the other sectors, with impacts on those possible and the likelihood of realisation. Furthermore, implementing options will put constraints on the development of the other sectors. Sector based analysis ignores system constraints imposed on concurrent and future provisioning and often overlooks the time dependency of provisioning on other sector benefits. By inclusion of dependency we more fully assess the interdependency risk and, by consideration of this, can explore more flexible decision pathways, using methods such as real options analysis (ROA). We therefore reduce the risk of investments, particularly at the concept design stage, where assumptions will be severely uncertain.

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<sup>a</sup> Environmental Change Institute, Oxford University Centre for the Environment, Oxford, OX1 3QY, UK  
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The aims of this work are: (i) to provide a framework capable of appraising multiple sector networks, capturing system impacts and allowing for different sequencing of provisioning options throughout time to make up a functional interacting system; and (ii) to provide a method to view these feasible combinations and their multiple benefits to support the process of decision making from a policy maker's perspective. This paper first sets out current appraisal practices within the sectors (section 2), before proposing a framework to extend methods to include interdependency and future flexibility in section 3. The framework is tested against a case study on the 'Thames Hub' vision in section 4, with conclusions drawn in section 5.

## **II. Current Appraisal Methods**

Appraisal processes aim to deduce solutions with the maximum utility for a given level of resource. In the case of private infrastructure investors, this resource may simply be monetary, through the use of straightforward financial assessment. However, as many infrastructure assets necessitate partial public funding, regulatory approval, and/or planning permission, further multicriteria analysis (MCA) or uncertainty analysis is often required.

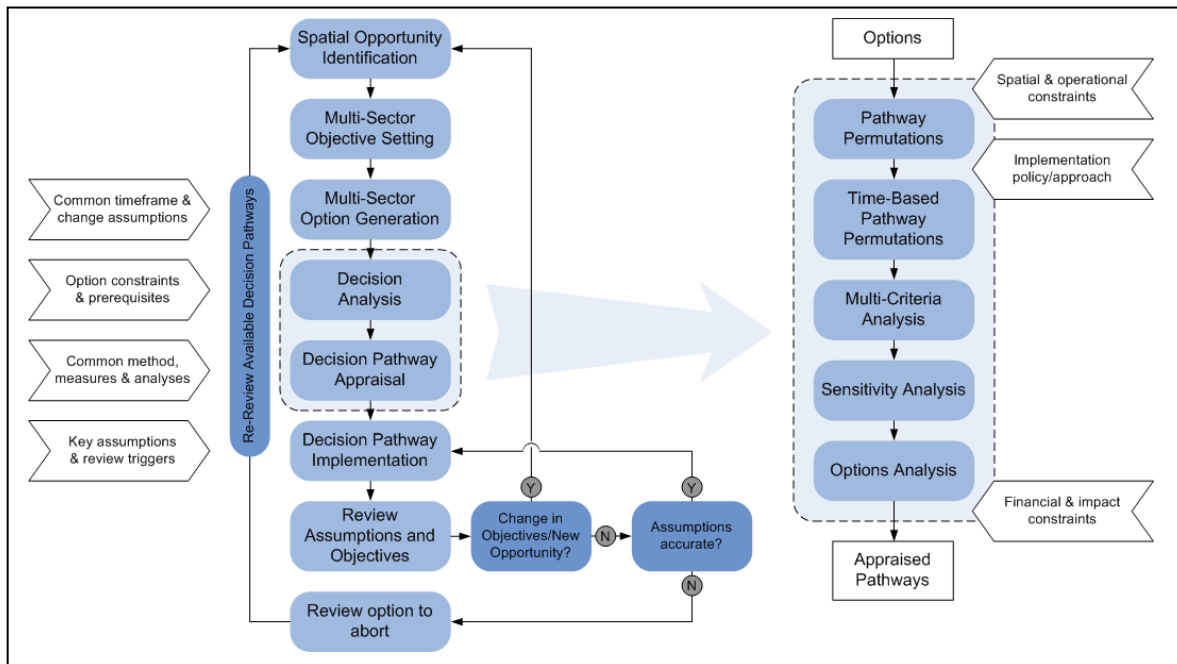
Both the water and transport sectors in the UK have structured frameworks, based on cost benefit analysis (CBA) and MCA. The Department for Transport's 'WebTAG' methodology, for example, is thought to be some of the most comprehensive transport appraisal guidance in the world<sup>4</sup>, and forms the basis of the World Bank's Transport Appraisal Toolkit. The timeframe (60 years), however, is still substantially shorter than that of the investments<sup>5</sup> and the assessment is almost entirely sector specific (energy demand is considered for tax and emission purposes). While both water and transport sectors consider multiple criteria, the methods are not easily comparable, leading to potential underfunding in some sectors<sup>6</sup>. Both sectors accept there is uncertainty in future system state conditions and use uncertainty analysis (and scenario analysis in the case of the water sector) to explore this. Yet no account is made of constraints placed on future provisioning, or the options these decisions hold for adaptation to changing conditions.

While the analysis outputs are specified to ensure consistency across proposals, they are still highly complex. For policy makers to move beyond their historical satisficing, methods must be more carefully communicated, with trade-offs and timeframes available for further exploration and future review against increasing levels of information<sup>7</sup>.

## **III. Inclusion of Flexibility and Interdependency**

Our framework builds on the existing sector specific MCAs. The framework is depicted in Figure 20 and can be summarised in four stages:

- Strategic review: Identification of cross-sectoral opportunities and necessary generic performance metrics;
- Pathway creation: Generation of options and application of interdependencies;
- Analysis: MCA and sensitivity analysis brought together in an option analysis and pairwise comparison with a cross-sector informed do minimum; and
- Review: Testing of assumptions, objectives and the decision pathway chosen as uncertainty diminishes.



**4. Figure 20. Proposed multi-sector appraisal framework.**

We propose a regional focus, with strategic opportunities and challenges identified spatially rather than sectorally. Performance metrics and methods are generic, developed to depict the realisation of cross-sector opportunities and high level regulatory requirements, but also to explicitly record the cross-sector demand requirements. Metrics are set to encompass multiple stakeholder viewpoints under four subject headings: environmental, service, social and economic/financial.

The analysis takes a long-term (100 year), severe uncertainty decision approach, drawing on the literature of robust decision making, using an adapted ROA. While real option assumptions have limited applicability for infrastructure investments<sup>8,9</sup>, these can be overcome, with ROA having been successfully explored in a number of single sector contexts<sup>10,11,12</sup>. However, its use in real-world infrastructure decision making is limited to date<sup>13</sup>. Here, we apply the pathway uncertainty analysis of ROA through uncertainty analysis of key system state variables and time dependency analysis of implementation. However, recognising the severe uncertainty at conceptual design stages, we combine these in a min-max decision pathway analysis, rather than compiling defined probability distributions.

It is recognised that some system state variables are coupled to the infrastructure investments made.

To initially simplify the analysis, these variables (population, carbon price, sea level rise and fossil fuel prices) are treated as exogenous; however key assumptions are identified (population and carbon price) and explored through uncertainty analysis. Land Use Transport Modelling can be used to further explore the interactions between the investments and the demand for their services. Interdependency is incorporated by explicitly recording the cross-sector demand and through consideration of constraints during the path dependency analysis. Here potential pathways are considered against the four interdependencies in Table 3. Spatial

and operational constraints are considered during the ‘pathway creation’ stage, with financial and impact constraints applied through thresholds after the options analysis (‘analysis’ stage).

#### 5. Table 3. Topology of interdependencies.

Interdependence	Resource Limitation
Spatial	Geographical location
Operational	Functional resource such as water, electricity, or skills
Financial	Funding available or revenue realized
Impact	Outputs such as emissions, noise or habitat loss

Finally, feasible pathways are displayed as a decision tree with min-max outputs and uncertainty levels collated under the four subject headings (see Figure 21). The output range is visible to the decision maker along with how this changes with each future decision taken. It highlights which constituent infrastructure options are key to the delivery of benefits, how these build up together across sectors and how the benefits are affected by the uncertainty of system state variables. It therefore recognises routes of high uncertainty and promotes the tracking key assumptions and identification of ‘trigger points’ where a change in direction should be considered.

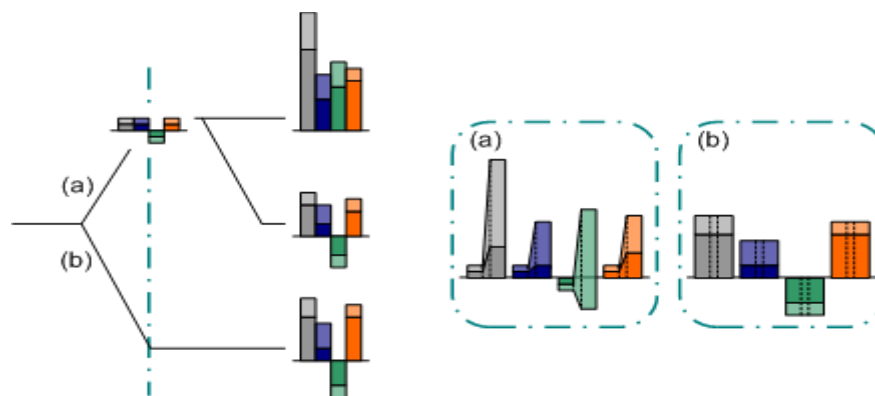
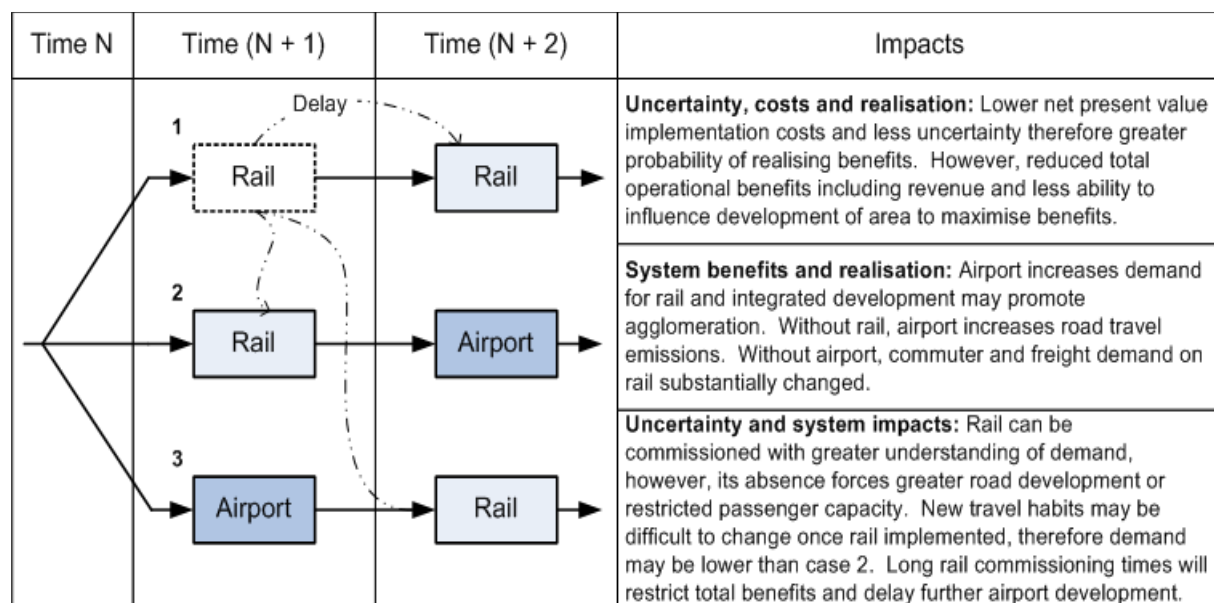


Figure 21. Pathway flexibility analysis.

### IV. Case Study on the ‘Thames Hub’ Vision

The framework has been applied to the ‘Thames Hub’ vision, a proposal for the development of an integrated infrastructure hub in the Thames Estuary, South East England. It includes a new hub airport, high speed and commuter rail lines orbiting London, a new Thames flood barrier and a tidal energy barrage. It therefore directly includes water (flood), transport and energy sectors, with implications for the communications, water (provisioning) and waste sectors. The time dependence of the element impacts and their interdependence is illustrated for rail in

Figure 22.

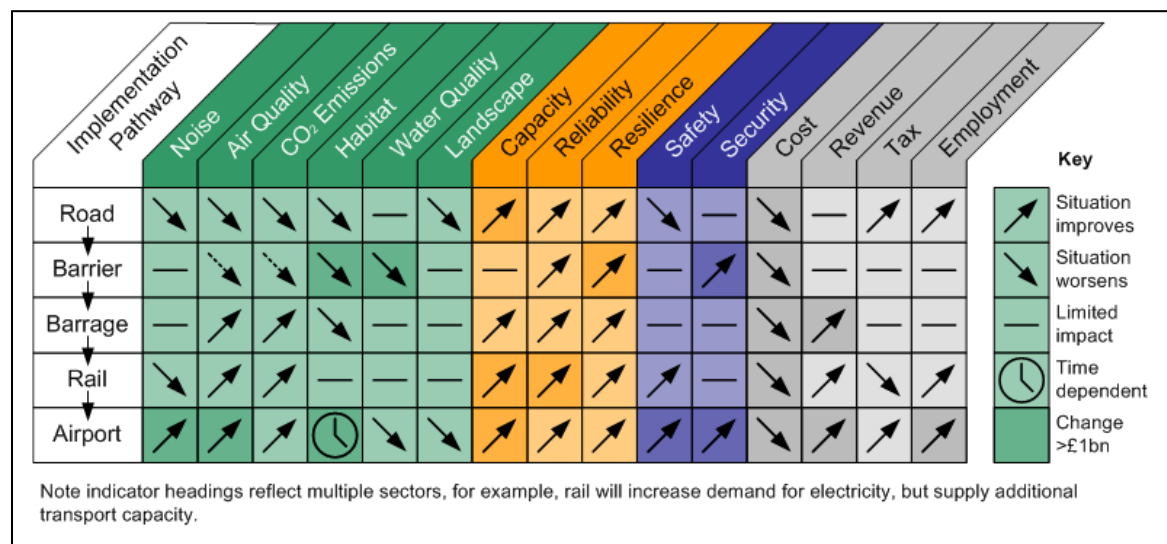


6.

7. Figure 22. Illustrative interdependence and time dependence of rail and airport impacts.

Sector performance metrics, were reviewed for the primary infrastructures and developed into 15 cross-sector metrics under the four subject headings. These are displayed along with an initial assessment of impact for a single pathway in

Figure 23. A full MCA of all pathways under different policy approaches is currently underway.



8. Figure 23. Single pathway MCA.

## IV. Conclusion

We argue that interdependency of infrastructure networks needs to be considered during appraisal to more fully capture the impacts and benefits realised and the risk profile of infrastructure investments. We posit that resilient choices are possible despite high levels of uncertainty, through the incorporation of these interdependencies within and adapted ROA

and the ongoing review of choices. We have proposed such a framework, that is capable of devising possible cross-sector infrastructure option combinations ('pathways'), analysing the time sequencing of their implementation and capturing the uncertainty of their impacts through sensitivity analysis, an adapted real options analysis and exploration through Land Use Transport Modelling. We have also proposed how this can feed into a decision support visualisation that displays the feasible combinations, their multiple benefits and how these vary through pathway 'families', to support decision making and ongoing review. In particular it enables understanding of the implications of when the investments are made, both due to the future uncertainty and through understanding how implementation policies affect the total benefits achieved. Further we have provided a consistent cross-sector methodology with generic performance measures that allows prioritisation across sectors where resources are constrained. The methodology has been applied to a case study on the 'Thames Hub' vision demonstrating the presence of system benefits and temporal characteristics that would be ignored through traditional valuation methods and the potential for development of cross sector performance metrics.

The framework is strategically focused assuming initiation at the concept design stage and the regional spatial scale. It is therefore limited by the information available at this stage and the amalgamation of data within this space. Further analysis of lower spatial and temporal scales would provide useful information on the interdependencies of infrastructure networks and is being conducted as part of the Infrastructure Transitions Research Consortium (ITRC), but is beyond the scope of this study. Future work will focus on further development of the case study option valuation and additional analysis of system state conditions, through use of the *ARCADIA Land-Use Transport Model*.

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# Evolving a climate-resilient electricity infrastructure in the Netherlands

L. Andrew Bollinger<sup>a\*</sup>  
Gerard P.J. Dijkema<sup>a</sup>  
Igor Nikolic<sup>a</sup>

**Abstract:** A resilient electricity infrastructure is one which preserves continuity of service despite perturbations in its environment, if it fails, it does so gracefully, not catastrophically. Electricity infrastructures globally are undergoing a low-carbon transition with a yet-to-be defined endpoint. What will be the impact of these transitions on network resilience? How can we steer them to foster resilience? This paper introduces results from a model exploring the evolution of the Dutch electricity transmission network under various transition scenarios. The model captures the development of this network as a result of the decisions of a set of boundedly rational agents, representing power producers and a grid operator. These agents make repeated decisions to (dis)invest in various types of infrastructure components, driving the evolution of the network. Using network analysis techniques, we evaluate the resilience of the resulting network topologies and identify key drivers of resilience

**Key words:** Electricity infrastructure; Climate change; Vulnerability; Simulation, Energy transitions.

## I. Introduction

Electricity infrastructures are complex globe-spanning socio-technical systems whose functionality depends on a relatively stable set of environmental conditions. As forcefully demonstrated by events such as the 2012 blackouts in India (620 million people without power) and Hurricane Sandy (8.5 million people without power), fluctuations in these conditions – whether in the form of droughts, hurricanes or floods – can spark disturbances with potentially devastating consequences. Insofar as climate change is anticipated to affect the frequency and severity of weather extremes, it poses a potential threat to our electricity infrastructures, from degrading their integrity and performance to inciting major blackouts.

Next to the emerging issue of electricity infrastructure vulnerability to climate change, unabating societal concerns about the broader consequences of a changing climate are driving a gradual shift in the global power sector from a reliance on fossil to renewable energy sources and from carbon-intensive to low-carbon technologies. Further fueled by the privatization and vertical de-integration of the electricity supply chain<sup>ii,iii,iv</sup>, and by technological developments in the areas of renewable and distributed electricity generation, this transition will have far-reaching and systemic impacts on the infrastructure as a

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<sup>a</sup> Faculty of Technology, Policy & Management, Delft University of Technology, 2600 GA Delft, The Netherlands

\*Corresponding author: Andrew Bollinger [L.A.Bollinger@tudelft.nl](mailto:L.A.Bollinger@tudelft.nl)  
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whole<sup>v,vi,vii</sup>). *How will a low-carbon transition affect the vulnerability of our electricity infrastructures to climate change, and how can we support the development of a climate-resilient electricity infrastructure?*

The vulnerability of electricity infrastructures to climate change is influenced by both the geographical configuration and topological structure of these systems. Systems with a large proportion of key components situated in heavily exposed areas will likely be more vulnerable to weather extremes, and structurally fragile systems will be more prone to amplify local disturbances into network-wide blackouts. In this paper, we explore (1) the consequences of various trajectories for a low-carbon transition on the geographical and topological features of an electricity infrastructure, and (2) the relationship between these features and the vulnerability of the infrastructure to certain types of extreme weather events that are anticipated to occur with increasing frequency as a result of climate change.

This paper introduces preliminary results from a model assessing the vulnerability of the Dutch electricity infrastructure to climate change, taking into account the various possible development trajectories of the infrastructure over the coming decades. As a low-lying coastal country located at the mouth of three major European rivers, the Netherlands is particularly exposed to sea level rise and riverine flooding, as well as to wind storm losses and extreme windspeeds<sup>viii</sup>— all of which may significantly affect the performance of infrastructure components. Moreover, the Dutch government has committed itself to a 20% reduction in carbon emissions by 2020 and an 80% reduction by 2050. Meeting these targets will necessitate a large-scale shift towards renewable and other low-carbon generation technologies and the realization of a transmission/distribution system capable of seamlessly integrating these technologies and continuously balancing supply and demand. While it is clear that a transition is necessary, we do not know precisely what form the future infrastructure will take.

## II. Positioning of the research

A growing body of research suggests that climate change is likely to influence the supply, demand, transmission and distribution of electricity in myriad ways. Increases in mean air and water temperatures and decreases in river flows are likely to affect the availability and efficiency of thermal and hydropower generators<sup>ix,x,xi</sup>. Growth in the frequency and severity of windstorms may increase the occurrence of downed overhead lines, and rising sea levels combined with increased frequencies of extreme rain events may lead to periodic flooding of low-lying areas and subsequent disruption of power substations. Higher average and extreme temperatures may increase demand for air conditioning and refrigeration, possibly leading to long-term increases in peak electricity loads<sup>xii,xiii</sup>.

While a significant body of research has elaborated on various weather/climate sensitivities of electricity infrastructure components, less is known about the vulnerability of infrastructure networks *as a whole*. To address this gap, our work builds on research in the area of *structural vulnerability analysis* of power networks. Central to this body of research is the notion of power systems as complex networks in which failures may propagate nonlinearly through the network, leading to critical thresholds in system performance. Beginning with a graph representation of an abstract or real-world power network, studies in this area assess how the successive removal of nodes/edges affects network

performance<sup>xiv,xv,xvi,xvii,xviii</sup>. This technique provides insight into patterns of degradation in system performance resulting from successive component failures.

In addressing the issue of electricity infrastructure vulnerability to climate change, we extend on this core approach of structural vulnerability analysis in several ways. First, we modify the sequence of node/edge removal so as to reflect component sensitivities to certain types of extreme weather conditions, specifically floods and windstorms. In this manner, we seek to capture extreme weather-induced patterns of network degradation, producing insight into the performance of the network under such conditions. Second, we test not a single network, but multiple networks representing different development trajectories of the Dutch electricity infrastructure. These networks reflect a range of possible futures, and are intended to capture uncertainties concerning the endpoint of a low-carbon transition.

### III. Approach

The purpose of the model described here is to assess the vulnerability of the Dutch electricity infrastructure to climate change, and to identify options for supporting the development of a climate-resilient electricity infrastructure. The model is composed of two submodels – a model of *infrastructure evolution* and a model of *infrastructure performance*. The infrastructure evolution submodel captures the long-term development of the Dutch electricity infrastructure under various scenarios, while the infrastructure performance submodel assesses the climate vulnerability of these “evolved” infrastructures.

*Infrastructure evolution submodel:* The starting point for the infrastructure evolution submodel is a dataset describing the current configuration of the Dutch electricity infrastructure, including generation and transmission/distribution. Four scenarios (plus a baseline) are used to describe the development of the generation portfolio over a period of 40 years. These scenarios (Table 1) have been selected to reflect a range of possible development trajectories for the Dutch generation portfolio.

Scenario	Description
Centralized generation	Continued growth in large, centralized, fossil-based generation facilities. Geographical consolidation of generation.
Distributed generation	Rapid expansion of renewables-based distributed generation, spread evenly across distribution grids. Commensurate growth in centralized generation to compensate for renewables intermittency.
Offshore wind	Rapid expansion of offshore wind in predefined North Sea locations. Commensurate growth in centralized fossil-based generation to compensate for intermittency.
Import	Gradual flattening in the growth of domestic supply, compensated by an increase in supply by neighboring countries
Baseline	Infrastructure remains unchanged from its current state.

**Table 1. Supply scenarios for the infrastructure evolution submodel**

The core of the infrastructure evolution model is an algorithm representing the decision making procedures of the Dutch transmission system operator (TSO) with respect to investments in new transmission capacity. Design criteria for the real-world Dutch transmission grid are laid out in the so-called *Grid Code*<sup>xix</sup>, established by the Dutch

Electricity Act of 1998. To ensure compliance with these criteria, the Dutch TSO carries out annual evaluations of the transmission grid<sup>xx</sup>. These analyses serve as a basis for the determination of necessary capacity upgrades. A simplified version of the TSO's assessment procedure guides capacity upgrades of transmission system components in the infrastructure evolution submodel. Each timestep during the course of a simulation (one timestep = one year), an algorithm performs a set of contingency analyses under peak demand conditions for a set of four scenarios with varying geographical distributions of generation dispatch and imports/exports. As a result of these analyses, necessary capacity investments are initialized to keep the system in line with the requirements of the Dutch Grid Code.

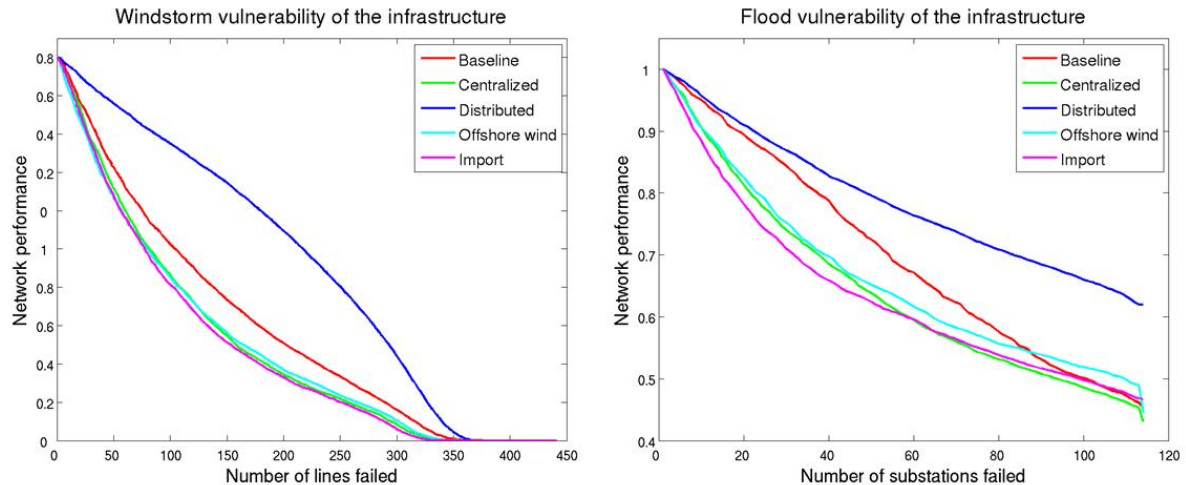
*Infrastructure performance submodel:* The infrastructure performance submodel assesses the performance of the Dutch electricity infrastructure under various types of extreme weather conditions that may be expected to occur with increasing frequency as a consequence of climate change. This assessment takes the form of a structural vulnerability analysis modified to reflect certain effects of these extreme weather conditions. For each of the topologies generated by the infrastructure evolution submodel – one for each scenario representing the final (2050) state of the infrastructure – the model executes two analyses. The first analysis involves the successive removal of random power lines, with the removal of each line followed by an assessment of network performance. The second analysis involves the successive removal of substations, also followed in each case by a performance assessment. Network performance is defined as the ratio of power delivered to power demanded. In calculating network performance, the model takes into account the possibility for cascading failures, which are an important aspect of power system vulnerability, and have played a role in some of the most notorious blackouts in recent years<sup>xxi-xxii</sup>.

The model captures the vulnerability of infrastructure components to two types of extreme weather conditions – *flood events* and *windstorms*. We have chosen to incorporate vulnerabilities to these types of extreme weather conditions given both their anticipated role in the context of climate change<sup>xxiii,xxiv,xxv</sup> and their potential to affect power system performance. Vulnerabilities of infrastructure components to both floods and windstorms are represented by adjusting the probability of component failure in the structural vulnerability analysis. In the case of flood events, the probability of substation failure depends on the elevation of the substation, and in the case of windstorms, the probability of line failure is proportional to line length. Failure probabilities do not currently account for adaptation measures such as dikes or pylon designs that may provide added protection to certain components.

#### IV. Key Results

Figure 1 illustrates key results from the infrastructure performance model, based on the averaged results of 100 simulation runs. In the tests of both flood and windstorm vulnerability, important differences can be seen in the patterns of performance degradation across the tested scenarios. In the windstorm analysis, the networks in most scenarios exhibit convex performance degradation – a sharp initial drop in performance followed by decelerating degradation with further failures. This pattern can be attributed largely to the centralized nature of production in these scenarios – by 2050 most supply is situated in a handful of coastal areas, resulting in a situation in which the failure of a few key lines can significantly cripple system performance.

The distributed generation scenario produces a very different result. In this case, the network exhibits slightly concave performance degradation, which can be attributed both to the decentralized nature of production and to the greater capacity of lines relative to the centralized and import scenarios. The decentralized nature of production means fewer “critical” lines whose failure engenders a plummet in system performance. Greater line capacities mean fewer failure cascades, since remaining lines are able to better handle the extra burdens of successive line failures.



**Figure 1. Windstorm and flood vulnerability for the different scenarios, based on the results of the infrastructure performance model.**

The flood performance analysis exhibits similar behavior. In this case, we see a maximum performance degradation of 50-60% in the centralized, import and offshore wind scenarios, resulting from the successive failure of 114 substations situated less than one meter above sea level. The distributed generation scenario performs better, with less than a 40% drop in performance under similar conditions. It is important to note that the smoothness of these averaged results conceals highly nonlinear behavior that may occur in individual runs. In some cases the failure of a single line or substation can cause a drop in network performance of 10-20% as the network reaches a critical threshold. These critical thresholds may be reached sooner or later, depending on the sequence in which lines or substations fail.

## V. Discussion and Conclusions

The results suggest that a future Dutch infrastructure based around distributed generation may help to mitigate electricity infrastructure vulnerability to climate change. However, this does not imply that a system based around more centralized generation is inevitably less resilient. The results suggest that much degradation in system performance arises from sudden and periodic large drops in network performance when the system reaches a critical threshold. Adaptation measures such as demand-side management and generation redispatch – which have been excluded from this analysis – could be employed in real time to alleviate stress within the network as these thresholds are approached. Harder measures such as dikes and pylon reinforcements can also help to inhibit the buildup of component failures. Future research will explore the potential benefits of such options and will explore the consequences of key assumptions underlying the presented model.

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# Resilience of resource movements to disruptive events

Shaun A. Brown<sup>a</sup>  
Richard Dawson<sup>a</sup>

**Abstract:** This research presents a quantitative resource model that embeds input-output relationships of supply and demand within a spatial network model. This allows the impacts of a spatial hazard on the movement of resources to be evaluated. The model enables scenarios and interventions to be explored to aid the development and design of effective infrastructure provision to sustain the resource needs of a modern society. The model has initially been tested on a case study in the Shetland Islands. The analysis highlights how a single flood event can disrupt the movement of resources across the region. Disruption of certain sectors can lead to a cascading failure across the system, which result from system interdependencies. Resource management strategies, such as storing supplies locally or alternative movement schedules are shown to increase the resilience of the system. Finally, planned model and case study developments are described.

**Keywords - Input-Output model; Network analysis; Resilience; Resource flows.**

## I. Introduction

As infrastructure systems become increasingly interdependent, the potential scale of disruption, the subsequent cascading disturbance of resource flows and the resultant impact on society becomes increasingly difficult to analyse. The approach taken within this research is a combination of elements taken from two differing approaches. The first is the use of an input-output (I-O) model taken from studies of infrastructural interdependence and second is the use of network theory to develop test of resilience within such infrastructural networks.

The need to understand resource movements has been highlighted by international events such as flooding of the Chao Praya River Basin, Thailand, in the summer and autumn of 2011. This event had wide-reaching effects on the production and supply of many goods: Thailand manufactures 25% of the world's hard <sup>1</sup>. Similarly the reduced level of energy produced in the wake of the Fukushima – Daishi power plant disaster slowed the supply of materials and supplies to downstream industries including car assembly plants in the Northeast of England <sup>2</sup>. However, disruptions are not always a result of natural hazards; in the UK in 2000, truck drivers protesting over fuel prices blockaded petrol refineries, paralysing fuel distribution and the country in a matter of days <sup>3</sup>.

## II. Resource Model

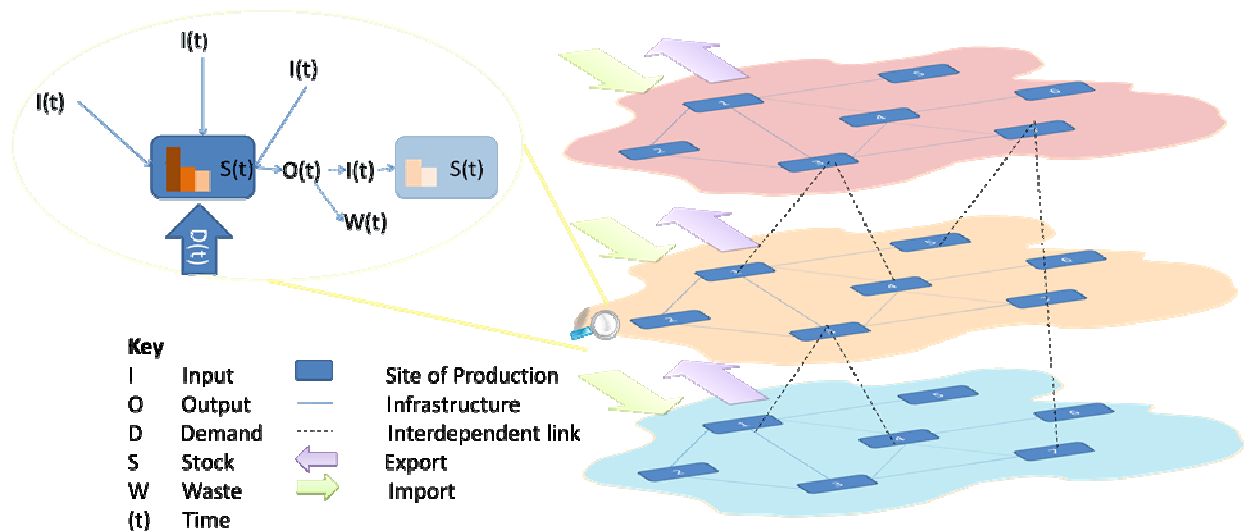
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<sup>a</sup> School of Civil Engineering and Geosciences, Cassie Building, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom . Shaun A. Brown ([s.a.brown@ncl.ac.uk](mailto:s.a.brown@ncl.ac.uk))



The resource model draws on two established modelling methodologies: (i) input-output modelling and (ii) network analysis. The input-output relationship depicts each sector's requirements from the other sectors in a system to produce one unit of its product<sup>4</sup>. Thus, it highlights the interdependencies between these elements<sup>5</sup>.

Infrastructure systems including transport, energy, water and waste mediate the movement of these resources. Because the elements of these systems interact with each other and with their environment; they can then be analysed using network theory<sup>6</sup>. To understand resource flows across these networks the traditional network modelling approaches have been expanded to capture inputs,  $I$ , outputs,  $O$ , as well as stocks,  $S$  and flows through time,  $t$ . For example (Figure 1), industry A requires  $x$  from industry B and  $y$  from industry C. whilst A supplies B, D and E with  $z$ . A disturbance in supply from B will disrupt production in A, which consequently cascades to industries D and E. The model enables a range of alternative resource management strategies to be explored, with evaluation of the effectiveness of these strategies taking place<sup>7</sup>.



**Figure 1. Future model development will enable the disaggregation of resource movements according to the networks they require and / or support.**

The current model assumes resources move along only a single infrastructure network connection. Building on work by Fu *et al.* (2012) and Dunn *et al.* (in press) this model is in the process of being extended to consider multiple networks of interaction, representing energy, water, transport and other interactions (Figure 1)<sup>8,9</sup>.

Each of the nodes within the network represents an industrial site and they are connected to other sites if an input output relationship exists. The magnified view in Figure 1, shows an industrial site that has three input; these provide a given quantity of a resource at each time step. In this instance, the singular output acts as an input for another industrial activity. The model also introduces the notion of reserve stocks that can stored at a given node.

The model has been implemented in the python programming language; the Numpy extension was used to facilitate the matrix analysis, required for the I-O analysis, and the

NetworkX extensions for the formation and operation of networks to support the construction and analysis of the network model<sup>10,11</sup>.

### A. Resource Flows Resilience Analysis

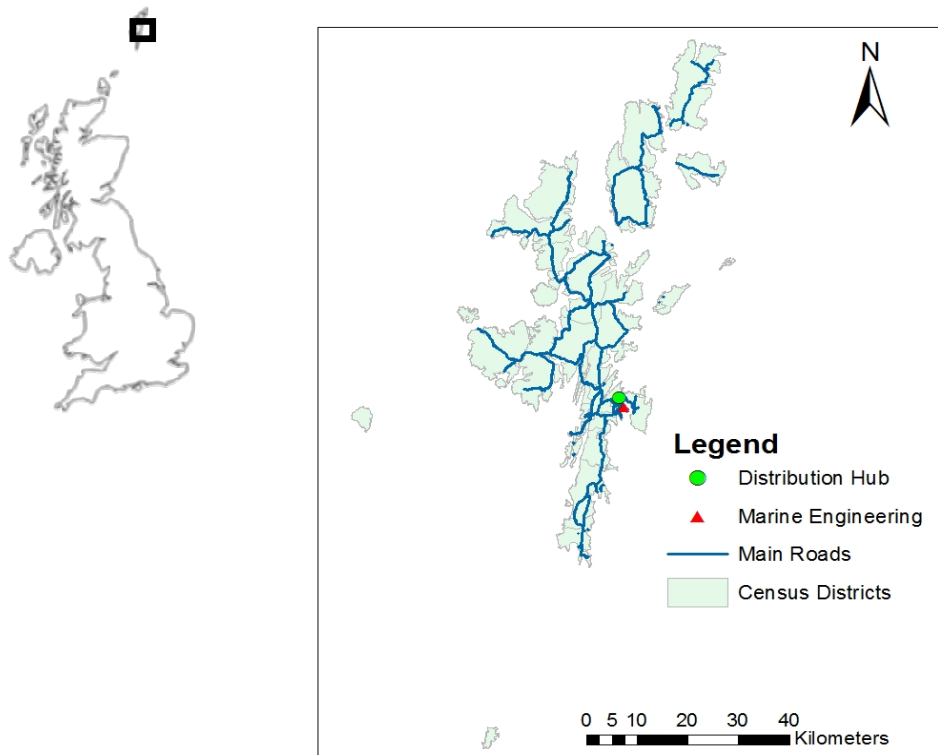
This study is not seeking to evaluate indirect economic impacts, so simple metrics were used to aid understanding of the interdependencies and the process of disruption, as well as compare the effectiveness of alternative resource management strategies<sup>12</sup>:

1. The number of time steps after the initial disruptive event before each site fails
2. The proportion of sectors operating
3. The number of remaining active input output connections

This latter measure is often used as a proxy to measure the resilience of networked systems<sup>13</sup>.

### B. Case Study

A preliminary case study, based upon data from the Shetland Islands was used in the case study and set up to test the model<sup>14</sup>. This preliminary analysis is based solely on local industrial interactions; therefore imports and exports to or from the islands are not taken into account. These study sites are suitable as the internal economy of the Islands is well documented and many of the industries, such as Marine Engineering and Distribution hubs (Figure 2), are co-located geographically which reduces the complexity of the spatial interactions that need to be represented in the model, facilitating interpretation and validation of the model.



**Figure 2. Map of the Shetland Islands and the location of marine engineering and distribution hubs.**

## III. Results

Here we compare the performance of four alternative strategies (S) for resource management when subjected to a disruptive event.

S1. Nodes can only receive deliveries of a single stock at each time step.

S2. As (S1), but each node has reserve stock of three units.

S3. ‘Batch deliveries’ of a chosen quantity and frequency of delivery – for example five units every fifth time step.

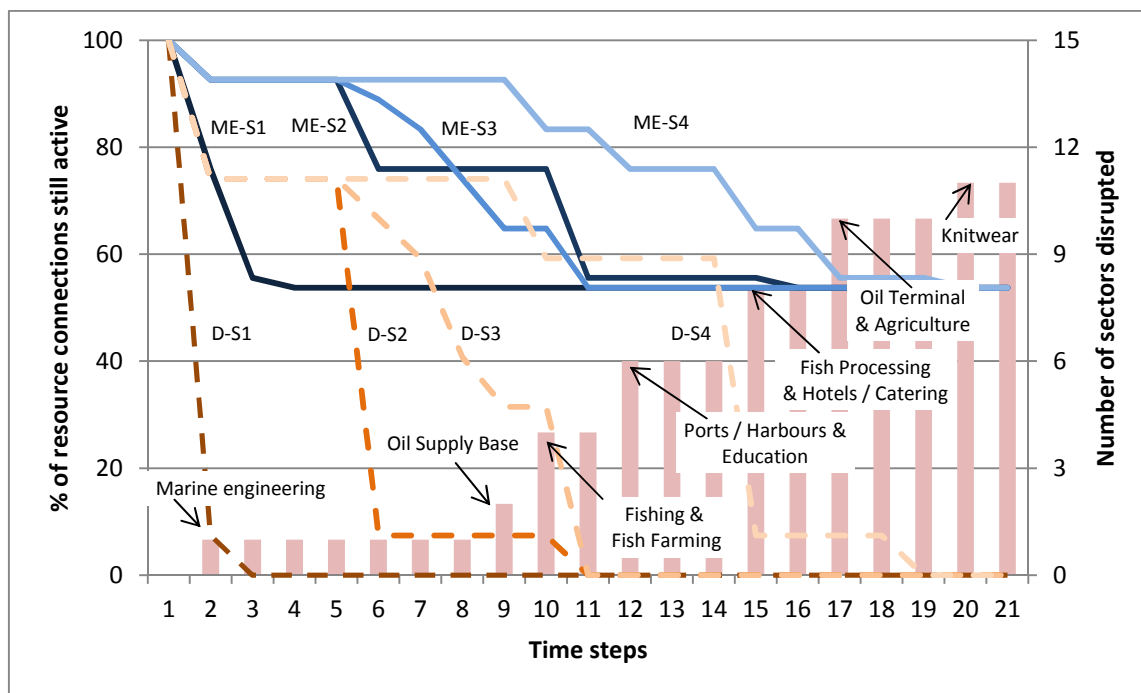
S4. As (S3), but each node has an additional reserve stock of three units.

Two disruptive events are considered:

1. The North and South Burn of Gremista, an area highlighted by the council as being at risk and home to Marine Engineering (ME) industries<sup>15</sup>.
2. Although distribution (D) hubs, also located near Lerwick, are located in a region that has previously suffered tidal flooding during “the Braer Storm” of 1993, the event assumed a wider snowfall blocking major transport routes across the Island.

In both events, activity on disrupted nodes was completely halted and existing stocks on these nodes were assumed to be destroyed *i.e.* the input and output links severed. Any subsequent impacts are a result of the system cascade.

S1 (Figure 3) for both ME and D show a quick cascading of disruption through the system although ME-S1 plateaus for a period. Due to its high connectivity and logistical importance, D-S1 shows an almost instantaneous and complete loss of resource flow across the island. Conversely, ME does not directly supply resources to key sectors and so total collapse from the event only occurs after many other sectors are choked of resources. In S2 an onsite stock is added providing a lag time between the events and cascading disruption, providing infrastructure operators, planners and business owners’ time to take corrective action increasing adaptive capacity and therefore resilience to such an event.



**Figure 3.** Lines show the proportion of resource connections that remain active after an initial disruptive event at  $t=0$  for resource management strategies S1-S4. The bars show the timing of sector disruption for the ME-S4 simulation.

A batch-deliver strategy employed in S3 can provide a further increase in lag if the deliveries are well-timed – which explains why ME-S3 at first seems to outperform ME-S2 but then drops off more rapidly: the quantity and frequency of deliveries has a large impact on resilience and this was supported by further sensitivity tests. Combining a bulk delivery pattern with stock reserves provides the greatest resilience of all the strategies considered here.

#### **IV. Conclusions and Future Developments**

It is vital to recognise and maintain the flow of vital food, materials, water and other resources to ensure community resilience, before, during and after any disruptive event. This paper has presented preliminary results and insights from a new resource model that couples information on consumption and demand for resources, within a network model. This has enabled us to understand resource flow disruptions in time and space.

The high degree interdependency of the distribution sector has a far greater and more rapid cascading disruption of the wider resource network, compared to a localised disruption of the marine engineering sector. A ‘Just-in-time’ resource production and movement strategy caused the fastest cascade through the system. On-site storage of stocks increased resilience to disruption, with bulk deliveries providing further stability in both cases, although this is dependent on both the quantity and frequency of the delivery. This increased resilience provided potential ‘breathing room’ for the identification of alternative mechanisms for safeguarding the continued supply of resources, as well as repairing disrupted elements.

The initial demonstration of the resource model has established its capability to explore the implications of differing resource management strategies during disruptive events. Further work will be done to extend the capability of the model and enable its application to more complex case study locations, and more sophisticated analysis of management strategies and disruptive events. For example, rather conveniently in the current study, industrial sectors are generally well-clustered spatially, reducing the complexity of spatial interactions. This will not hold in most instances where production and consumption sites are located much more heterogeneously. Current work is extending the model into a more detailed spatial representation of multiple interacting infrastructure and resource networks.

The focus here has been on road-based resource movement, but current work involves integrating resource movements associated with water, electricity, gas and waste which have different spatial interactions, behaviours and potential resilience strategies (e.g. onsite generation). Consideration of waste flows will allow us to identify opportunities for greater resource efficiency. Additionally, an exploration of a much wider range of scales of disruption, rather than just the 0% or 100% performance explored here. Events that manifest over different spatial scales and intensities will also be explored – for example, flooding of multiple sites or a large snowfall that blocks multiple transport routes simultaneously. Furthermore, a consideration of more sophisticated resource management strategies, differing where supplies come from, dynamic switching of supply, local production (e.g. of energy or food) and recovery strategies to explore mechanisms that most effectively restore resource flows. Validation of the model, although difficult as it is essentially modelling human behaviour, will use a combination of sensitivity analysis and comparison to documented events, such as the 2000 UK fuel crisis<sup>16,3</sup>.

### Acknowledgements

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# How Do We Ensure the Assessment of Infrastructure Resilience is Proportionate to the Risk?

Matthew Holmes<sup>a\*</sup>

Anna Provost<sup>b</sup>

Derek Clucas<sup>b</sup>

Sean Wilkinson<sup>a</sup>

**Abstract:** As infrastructure becomes increasingly integral to daily lives, society becomes more vulnerable to potential failures. We mitigate against this by investing some of the increased prosperity afforded by infrastructure to treat the most salient risks and increase the resilience of the system. Therefore we enter a cycle where our ability to identify and prioritise vulnerabilities is crucial to the future development of infrastructure. It is easy to compose a list of risks occupying the whole spectrum from probable through to fanciful, but, how do infrastructure owners define defensible boundaries between the credible risks they should assess and those that can be set aside? This paper tests the hypothesis that incorporating information on the uncertainty of risk assessments provides risk managers with a more robust process to justify their choice of credible risks.

**Key words:** Infrastructure; Resilience; Risk assessment; Risk management; All-hazards

## I. Introduction

There is increasing evidence to suggest that infrastructure and sustainable development are tightly coupled. Effective and efficient infrastructure encourage economic, environmental and social development<sup>1,2</sup>, while development creates the demand for better infrastructure and, importantly, the means by which to afford it.

Which factor is the chicken and which the egg has caused much debate among economists<sup>3,4</sup> but the coupled nature of these factors is central to an emerging challenge for risk managers as Figure 1 illustrates. The cycle of development and infrastructure provision is shown in solid lines. As infrastructure becomes increasingly integral to our daily lives we become increasingly vulnerable to its failure, and thus it must be more resilient (the base of the dashed cycle). The role of infrastructure owners and operators is to mitigate the risks to their system in order to achieve this continual improvement. Naturally there is a preference (as with any decision) to treat the more salient and certain risks<sup>5,6</sup> but as the cycles in Figure 1 continue these risks are eliminated and infrastructure providers are obliged to consider increasingly obscure, complex and tricky risks.

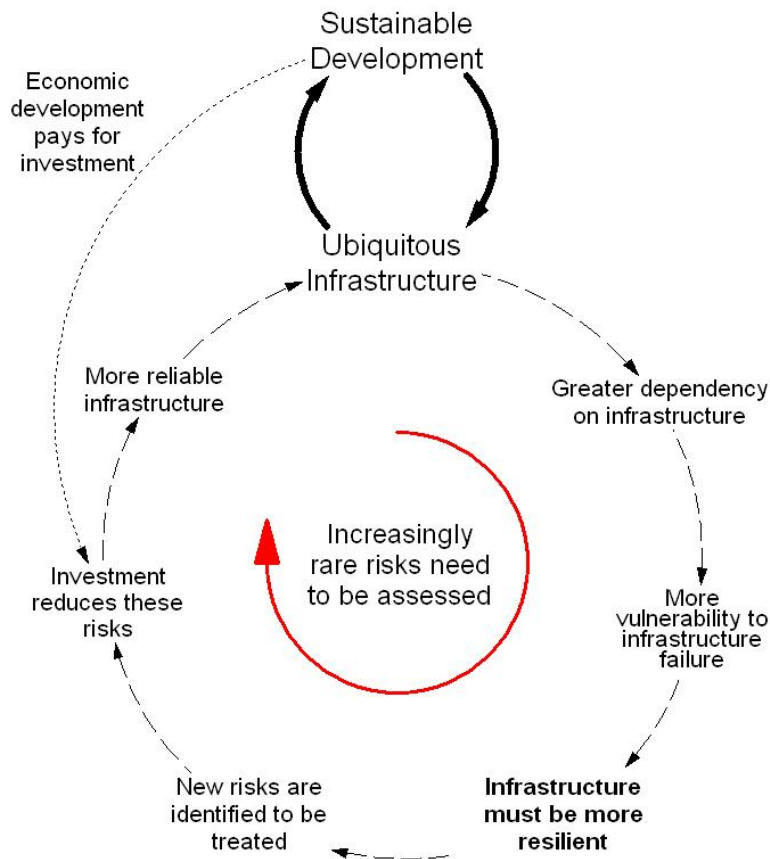
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<sup>a</sup> Civil Engineering and Geosciences, Newcastle University, Newcastle-upon-Tyne, NE1 7RU

<sup>b</sup> United Utilities Plc, Lingle Mere Business Park, Warrington, WA5 3LP

\*Corresponding author: Matthew Holmes [matthew.holmes@stream-idc.net](mailto:matthew.holmes@stream-idc.net)  
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Of course this cycle is not operating in an environment with unconstrained resources and because infrastructure owners and operators' budget are limited they need to target their investment carefully). In the aftermath of an event and with the benefit of hindsight it is easy to criticise owners and operators for failing to identify and act upon a risk. This is one reason for the growing impetus behind 'all-hazards' approaches to resilience<sup>7,8</sup>. It is equally easy to compose a long list of risks, occupying the whole spectrum of plausibility, which could conceivably affect an infrastructure system. But neither hindsight nor long lists are of value to a risk manager; infrastructure systems are large, complex and have many interfaces with other systems making risk assessments time-consuming and expensive. To ensure the effort of assessment is proportionate to the risk, managers must choose at an early stage which risks they can afford to assess in detail and set aside those they cannot.



**Figure 24. The addictive cycle of infrastructure resilience.**

These decisions – often made with little available information - are pivotal to the analysis and errors of choice can easily result in catastrophic consequences if the wrong risks are selected. Moreover, these errors might then be hidden from immediate view because they are not made in the analysis but in establishing the problem. Risk managers must be careful to avoid these errors since their decisions need to be defensible under an inquiry from senior management and regulators, and under public scrutiny if risk becomes reality. Therefore they must be systematic in choosing which risks to include and which to set aside. This paper assesses three approaches to making these decisions which employ different levels of complexity to explore the balance between the information provided to the decision maker and the costs of obtaining this information.



## II. Approaches to selecting risks

### XIX. Likelihood versus consequence

The obvious approach is to make a precursory assessment of the risk, considering the consequence and probability of occurrence<sup>9</sup>. Figure 25 is a useful diagram produced by the UK Cabinet Office<sup>10</sup> in 2010 which plots major risks according to these two factors. Can a risk manager choose which risks to assess based solely on this information, for example by excluding risks above the dashed line?

The benefit of this approach is its simplicity; it matches the approaches that risk managers are used to taking and those expected by regulators. It is recognised the placement and shape of the dashed line is potentially contentious but deliberately excluded from the scope of this paper for this and the two subsequent approaches discussed below. Ultimately it reflects the risk appetite of the utility provider and therefore will always be an individual choice.

The main challenge to this approach is that it does not account for the uncertainty attached to each assessment or the relevance to different types of infrastructure. The complexity of infrastructure systems means there will always be errors in the assessment of impacts and likelihoods. Moreover, this level of uncertainty varies between different risks; some are simpler or have been studied in detail whereas others are more complex and vague. Aleatory uncertainty is also a factor; events show natural variation meaning risks due not occupy a single point. This is well illustrated in IPENZ's New Zealand equivalent of Figure 25<sup>11</sup>.

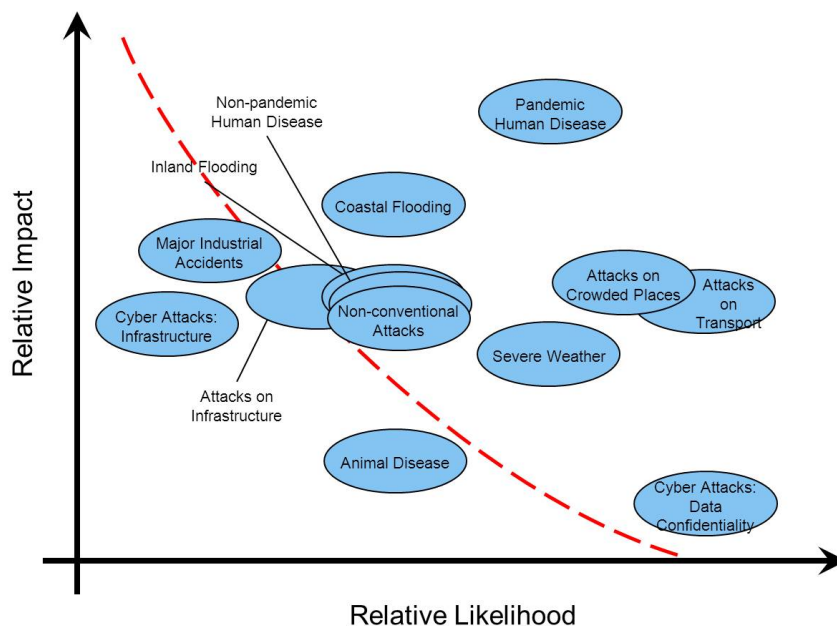


Figure 25. High consequence risks facing the United Kingdom.<sup>11</sup>

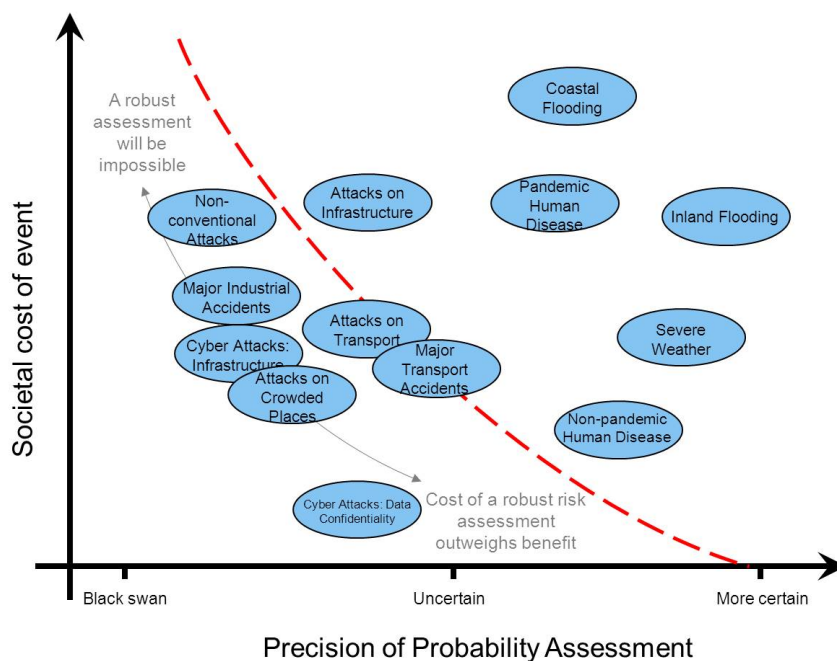
### XX. Subjective assessment of uncertainty

It is logical that risk managers should seek to account for this uncertainty as they select which risks to analyse. As a risk assessment become less certain it offers risk managers less information and therefore its value diminishes. In parallel, higher uncertainty makes risk assessments increasingly difficult and expensive. Accepting that they are working with finite

resources – and that all uncertainty will never be eliminated – a trade-off must be made between the cost of assessing the risk and the value of the information the assessment will provide.

We can get a new perspective by taking the concept from Figure 25 and replacing the likelihood with the uncertainty around the probability assessment. Risk managers can then use the expert judgement available to them to populate the diagram with potential risks. For example, they can assess day-to-day operational risks such as burst pipes with relative accuracy; they realise that some conventional risks, such as flooding, are uncertain but still feel they can reach a sensible estimate; and they acknowledge there are some risks which are too uncertain to reach a credible estimate, for example war or solar flares. An example is shown in Figure 26.

In the same manner as the dashed line in Figure 25 a threshold can be added to this approach to delineate which risks are worth assessing. The value of the information provided is influenced by the size of the risk (hence the curved line). There is little value in an uncertain estimate of a low risk but a similarly uncertain estimate of a high risk will have greater value; because the stakes are higher a decision maker may be more cautious and act on less certain evidence. The line approaches vertical as scenarios become too far-fetched for executives, shareholders and regulators to find them credulous. At this point we are entering the territory of ‘black swan’ risks as outlined by Taleb<sup>12</sup>.



**Figure 26. The limit of resilience planning set by the precision of the probability assessment.**

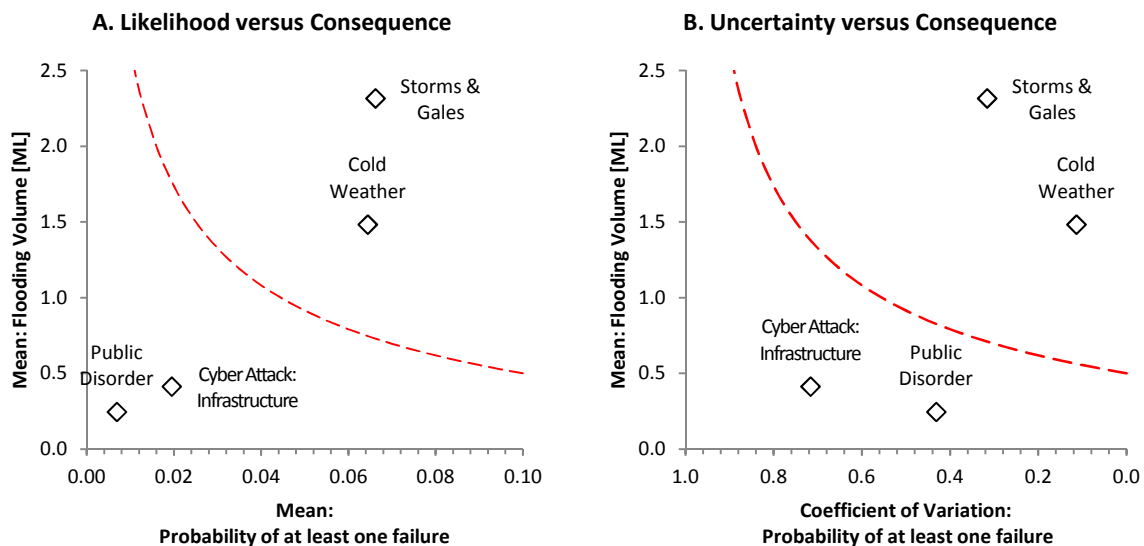
The challenge to this approach is that it is subjective, based upon a personal or organisational perspective of the risks and for rare risks they are likely to have no experience of the event. There will be inconsistency between different infrastructure providers and between them and regulators. This creates a significant risk for providers if their processes come under scrutiny.

## XXI. Formalised assessment of uncertainty

It is anticipated that by formalising the estimate of uncertainty the process becomes more transparent and therefore more accountable so this hypothesis is tested on a model of a real-world wastewater system. For the purposes of illustration four different risks – public disorder, storms and gales, cold weather, and cyber-attacks on infrastructure - are selected from the latest UK National Risk Register<sup>13</sup>. Basic event trees are then used to estimate the probability of the national scenarios having an impact on this particular network. Where a probability within the fault tree is subject to uncertainty a probability distribution derived from expert knowledge is used in the place of a deterministic value. 1000 realizations of the model are then used to assess how this uncertainty affects the risk of flooding.

- 1) For each realization the probability of at least one failure as a consequence of the scenario is calculated, the mean of these gives the likelihood shown on the x-axis.
- 2) The coefficient of variation, shown on the x-axis, is calculated as the standard deviation of the probability of at least one failure divided by the mean probability of at least one failure. Note the reverse scale on the x-axis.

A comparison between the results of this method and an assessment of only likelihood and consequence indicates that it does present new information, showing that the threat of cyber-attacks is highly uncertain and that public disorder could be assessed with relative ease. This is a useful outcome from the perspective of an audit trail demonstrating to others that a robust process has been followed; however, it does not materially affect the outcome of the assessment; that storms and gales and cold weather are the principal risks, and cyber-attacks and public disorder should be discarded from a proportionate risk assessment. In addition, whilst the process may make the subjective choices less opaque we have not addresses the accuracy of these expert judgements, in particular the difficulties of estimating the probability distributions of rare events. Therefore we return to the issue of balancing information and the effort of collecting it; does the benefit of the audit trail exceed the extra costs incurred in assessing the uncertainty even at a basic level?



**Figure 27. Comparison of likelihood versus consequence and formalised uncertainty versus consequence approaches.**

### III. Discussion

Three different approaches have been used to identify which risks are most important for further analysis. The simple assessment of likelihood and consequence benefits from its simplicity and it matches the expectations of regulators and policy makers. The omission of uncertainty at the risk screening phase is not a flaw in itself; however, its inclusion does present risk managers with an opportunity to justifiably eliminate those risks whose assessment adds little value. The second approach, subjective assessment of uncertainty, achieves this based upon the personal opinion of the assessor. The benefit of this is that it can be undertaken with limited extra input however it becomes an opaque process and its worth for very rare events is questionable. The third option which formalises the assessment of uncertainty increases transparency but increases the complexity and therefore cost of making the decision and still relies on the judgement of experts. This extra cost undermines the approach's purpose as a simple precursor to enable a more proportionate detailed risk assessment and, given the results also suggest that it offers little extra information compared to the simpler analyses, it is tempting to discount it. However the extra cost may be justified by its auditability and the possibility of easily updating the analysis as new assessments of risk come to hand.

It is also tempting to suggest the value of the likelihood versus consequence approach is limited by its simplicity. Whilst it provides a useful initial estimate of the risk it does not account for the effort which a risk manager will have to expend to convert this estimate into a more reliable assessment.

### IV. Conclusion

As reliance on infrastructure increases so does our vulnerability to failure, requiring risk managers to consider increasingly rare risks. This problem of dealing with very rare threats is only going to get worse and, due to the cost of assessing such risks, new and robust methods of identifying which risks should receive the most attention are vital. Incorporating high level subjective information on the uncertainty of the probability estimates allows them to do this in a more perceptive way, though subjective and opaque. Formalising this process by estimating the uncertainty of individual elements improves the auditability of this process but the extra complexity and cost may exceed the value of the new information obtained.

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# Analyzing Interdependent National Infrastructure Provisions Under Extreme Climate Risk

Raghav Pant<sup>a</sup>  
Scott Thacker<sup>a</sup>  
Jim W. Hall<sup>a</sup>  
Stuart Barr<sup>b</sup>  
David Alderson<sup>b</sup>

**Abstract:** To create sustainable, adaptive and resilient societies we need to develop a proper understanding of infrastructure risk. This research improves such understanding by examining widespread failures of interdependent infrastructure networks from extreme climate events. By subjecting infrastructure networks to extreme climate loading, we construct ensembles of direct failure sets that lead to cascading indirect failures across topological infrastructure networks. Such analysis produces two results: (1) Estimations of the topological fragility of infrastructure networks, and (2) Infrastructure vulnerability quantification in terms of spatial affects on service provision and customers using networked infrastructures. Producing multiple failure sets provides a wide range of possible outcomes, helping to build infrastructure failure profiles. Insights from risk analysis strengthen our understanding of infrastructure failures and are used to inform resilience-building activities for effective infrastructure provision.

**Key words:** Infrastructure risk; Interdependence; Climate hazards

## I. Introduction

Infrastructure sustainability, adaptation or resilience is better understood by examining national infrastructure risk. In the context of this research, national infrastructures represent civil and technological structures that provide goods and services to industries, governments and households operating at regional and national scales. In particular infrastructures such as electricity, gas, rail, road, and ICT are among critical national infrastructures, constituting the backbone of society and economy<sup>1,2</sup>. For better performance and service provision national infrastructures are highly interdependent systems through physical, technological or economic mechanisms<sup>3</sup>. Though interdependencies are desirable for maintaining infrastructure functionality and service delivery, they become disadvantageous during widespread failures, which result in failure cascading effects that propagate damages from one infrastructure to another<sup>4</sup>.

Extreme climate events put national infrastructures at risk because they are capable of causing widespread social and economic losses. Notably extreme hurricanes in the United States, floods in United Kingdom, and extreme heat in Australia have highlighted the large-

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<sup>a</sup> Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX1 3QY, UK, [jim.hall@eci.ox.ac.uk](mailto:jim.hall@eci.ox.ac.uk)

<sup>b</sup> School of Civil Engineering and Geosciences, Newcastle University, Newcastle Upon Tyne NE1 7RU, UK.  
<http://dx.doi.org/10.14453/isngi2013.proc.35>

scale vulnerabilities of national infrastructures provisions<sup>5,6,7</sup>. National scale climate change risk assessment policy statements have emphasized the imminent risks to critical national infrastructures in the present and future<sup>8,9</sup>. Climate risk modeling is inherently complex due to systematic uncertainties that propagate from extreme climate hazards towards infrastructure responses and failure impacts<sup>10</sup>. For critical national infrastructures a system-of-systems (SoS) approach is required for modeling escalating failures that affect multiple systems and multiple participants<sup>11</sup>. In this paper we present a SoS framework where infrastructures represent systems of interdependent spatial networks that are exposed to probabilistic extreme hazard scenarios.

Infrastructures are spatially distributed systems spread over large geographic areas. Further there are several components or assets within each infrastructure and across infrastructures that are connected physically or through flow of information. As such an overall spatial network topology can be identified to build a unified representation of infrastructures<sup>12</sup>. Extreme climate loading conditions initiate random failures of network assets and the topology determines the further propagation of these failures across entire networks<sup>13</sup>. Following network damages the SoS risks are quantified in terms of the consequences in terms of spatial damage impacts, demographic disruption impacts and interdependent economic loss impacts<sup>14</sup>.

The climate risk analysis methodology proposed in this paper aims to compute the overall risk of failure of infrastructure networks when exposed to multiple probabilistic climate hazards. By subjecting infrastructure networks to extreme climate loading, we construct ensembles of direct asset failure sets that lead to cascading indirect failures across topological infrastructure networks. Such analysis produces two results: (i) Estimations of the topological fragility of infrastructure networks, and (ii) Infrastructure vulnerability quantification in terms of spatial affects on service provision and customers using networked infrastructures. Producing multiple failure sets provides a wide range of possible outcomes, helping to build infrastructure failure profiles. Insights from risk analysis strengthen our understanding of infrastructure failures and are used to inform resilience-building activities for effective infrastructure provisions.

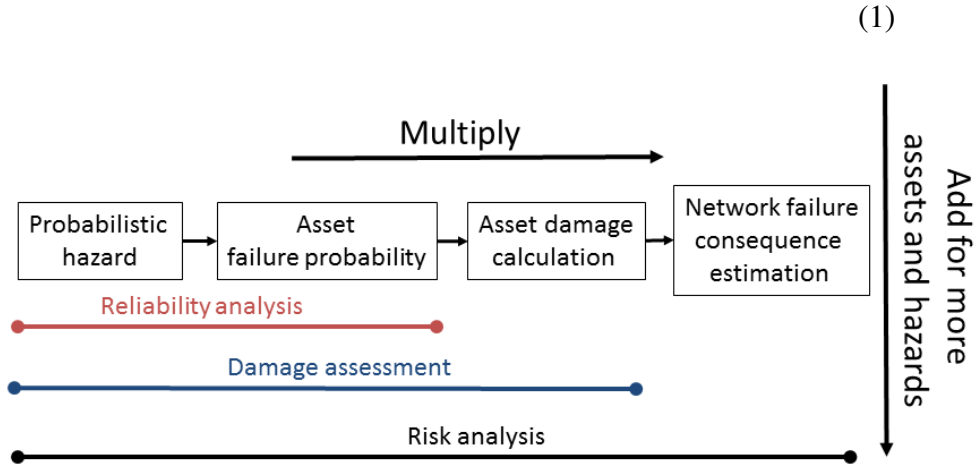
In the sections that follow we first explain the formulation for calculating interdependent infrastructure risk for extreme climate hazards. Next we present the underlying SoS framework that needs to be constructed for implementing the different components of the risk calculations. This is followed by a sample case-study demonstration for a national-scale network and hazard.

## **II. Quantifying infrastructure risk**

Infrastructure risk is broadly quantified as the product of the probabilities and consequences of network failures conditional upon probabilistic extreme climate hazards<sup>10</sup>. Within the context of this paper, reliability is the measure of the probability of failure, which is studied at the individual assets level and then at the infrastructure network level. For damage assessment the focus lies in estimating the customer losses and infrastructure output degradations, which ultimately are converted to economic losses at appropriate individual asset, network or national-scale levels.

Probabilistic extreme climate loading is quantified in terms of its spatial magnitude vector and joint probability distribution . To calculate risk we first represent an individual infrastructure asset functionality through a state function , such that denotes a ‘failed’ state and denotes a ‘non-failed’ state. Also we define two variables: (i) : The conditional probability of failure of an asset (*fragility*) when subjected to the external hazard loading , (ii) : The damage associated with the failure of the asset. For the entire infrastructure network, consisting of assets, functionality depends on all the asset states collected into a binary vector , whose elements are either 0 or 1 describing which assets have failed and which have not failed. In particular network reliability, damages and risk depend upon the elements in .

When exposed to the hazard there are many possible failure combinations of assets that result in network failure. In the most exhaustive scenario there are possible failure state combinations, but in reality fewer combinations can capture most of the failures. The vector defined before represents just one of the possible failure states and is defined here as a *failure mechanism*. We define the vector to represent the failure mechanism and the tensor as the collection of failure combinations that contribute to overall network failure. The infrastructure network risk ( ) formulation proposed in this paper is based on: (i) estimating the combined asset failure probabilities ( ) and damages ( ) due to multiple failure mechanisms, and (ii) repeating the calculations over multiple hazard loadings . This is shown in Equation (1) below and summarized in Figure 1.



**Figure 1. Framework for risk calculations required in the network failure analysis.**

### III. Risk implementation

Figure 2 shows a detailed flowchart for constructing component models and implementing a national infrastructure risk calculation framework that solves Equation (1). The important components in the flowchart are explained as follows:



1. **Hazard estimation (Component A):** Different types of extreme climate models can be built to estimate hazard severity ( $\mathbf{h}$ ) and uncertainty ( $\mathbf{h}$ ). Some of the models (Hazard extent maps/Spatial distributions of hazards/Spatial-temporal distributions of hazards) that are used in this framework are shown in the component A.
2. **Network estimation (Component B):** Topological network representations are essential for generating failures and computing failure probabilities ( $\mathbb{P}[r_i^j|\mathbf{h}]$ ). In this framework networks are built from information on the geo-locations of assets and their physical connectivity to other assets and networks.
3. **Network reliability analysis (Component C):** Reliability analysis provides the framework for building failure mechanisms, which leads to the computation of asset and topological fragilities, and ultimately the network failure probability. In this framework direct failures simulated by Monte-Carlo based approaches and network connectivity are utilised to estimate resulting topological failures.
4. **Infrastructure damage assessment (Component D):** Damages are quantified spatially by first constructing *infrastructure footprints* that estimate the number of customers served over the area influence of assets. Following this the direct and indirect spatial and demographic impact effects for asset damages and network losses can be quantified by assembling the footprints of all failed assets. For economic analysis purposes, the total network damage effects constitute direct economic losses due to infrastructure asset failures.
5. **Economic damage (loss) assessment (Component E):** The supply and demand side loss inputs are fed into an economic input-output model. Using the economic input-output analysis to find the disrupted equilibrium state we can generate the indirect losses and total losses ( $D(r_i^j)$ ) due to the network failures.
6. **Risk calculation (Component F):** Network risk  $R(\bar{\mathbf{r}})$  is computed when the reliability and damage estimations are implemented over multiple failure mechanisms and multiple hazards.

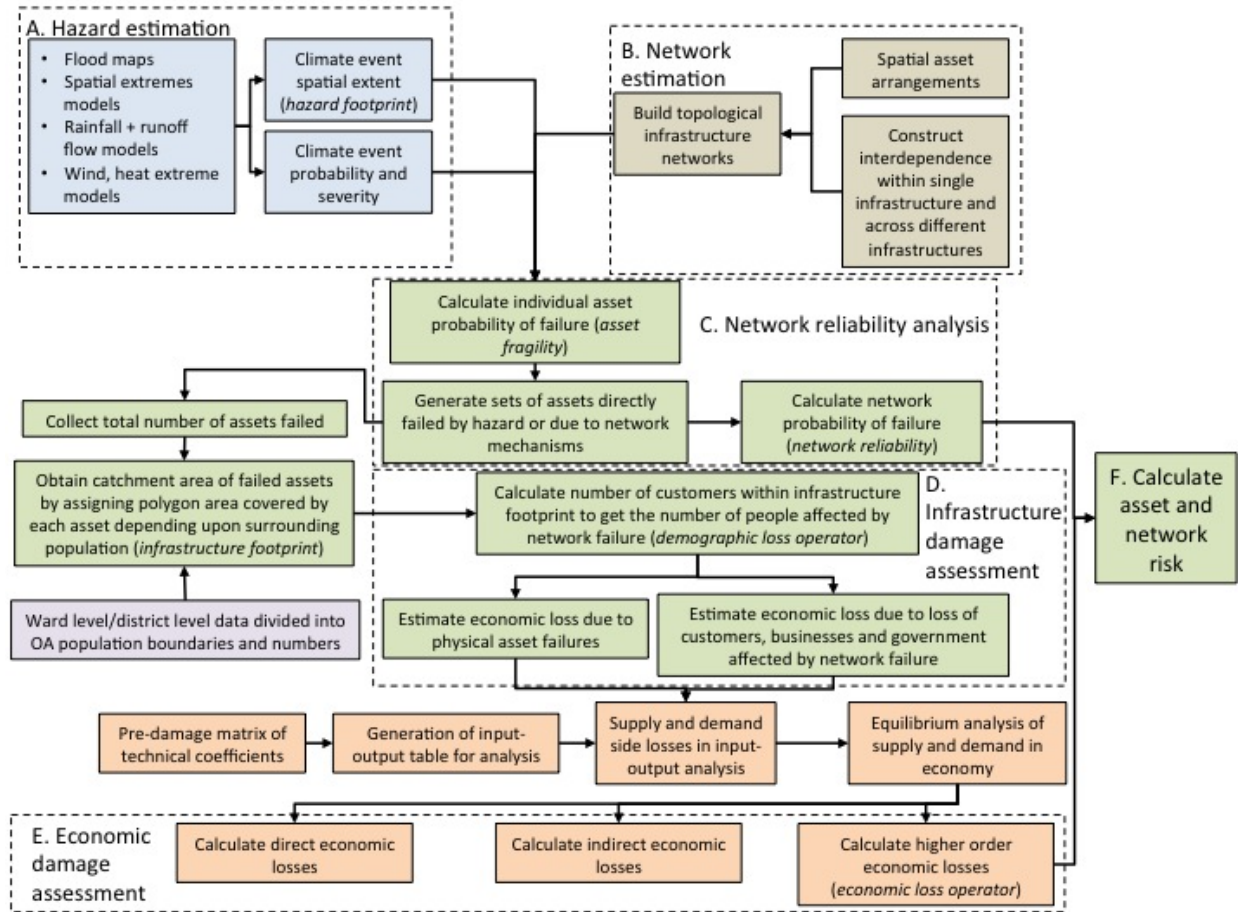


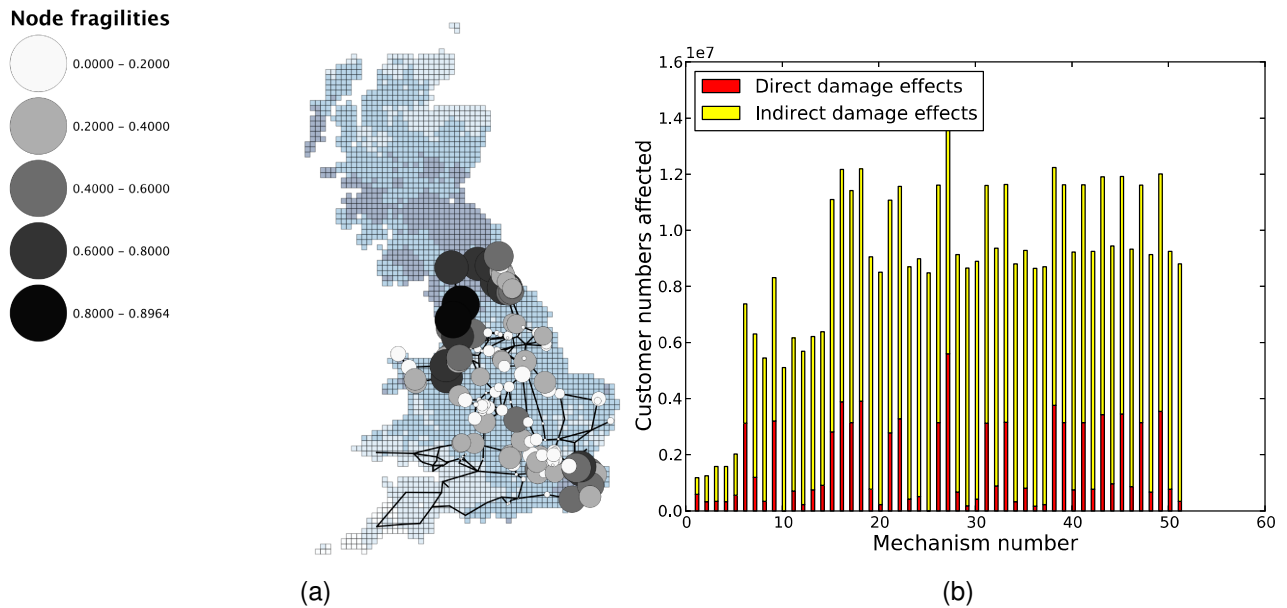
Figure 2: Flowchart showing steps in the ITRC WS2 Phase 2 infrastructure risk analysis.

#### IV. Case-study demonstration

Obtaining high quality data for the different components of the risk framework is very challenging, so models are employed wherever necessary. The case-study results shown here are synthetic but serve the important purpose of providing a template for risk calculations when real data is available. The risk methodology outlined in the sections above is implemented for simulated probabilistic hazard events that affect a sample topological electricity network for Great Britain. The network is a satisfactory topological representation of the actual electricity transmission network for Great Britain<sup>15</sup>. Further, the network nodes represent electricity substations that served customers over regions estimated from population census data<sup>16</sup>.

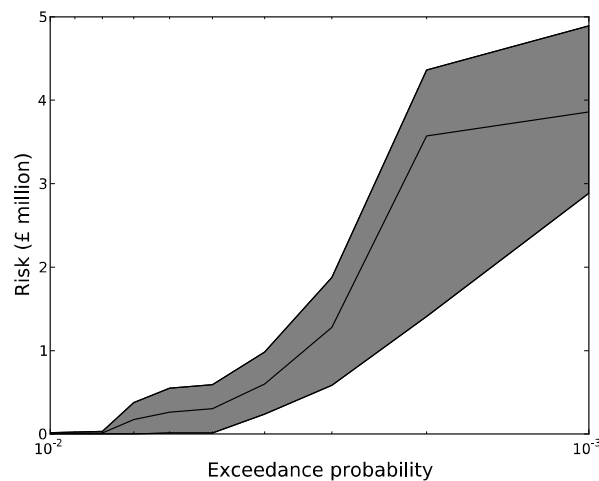
Figure 3(a) introduces the test network with nodes (substation) fragilities, magnified according to their relative values, after being intersected with a sample probabilistic spatial hazard event. This result is obtained by implementing the components A, B and C from the framework Figure 2. Using Figure 3(a) we can identify the substations that are at most risk of failing. Based on the node fragilities and resulting network behaviors we can generate a sample of different possible failure mechanisms. This is shown in Figure 3(b) where the resulting damages in terms of customers affected are calculated for each direct and indirect

failure mechanism. Hence, we are also able to obtain a range of possible risk outcomes from the analysis.



**Figure 3. Figures showing (a) The network node fragilities (color coded and weighted by magnitude) for a particular hazard event, (b) Sample failure mechanisms and direct and indirect customers affected.**

Another outcome of the analysis is shown in Figure 4 where the ranges of risks (in £ millions) are calculated for multiple mechanisms across different hazard events (given by their exceedance probabilities). This result is obtained by executing the components D and F in the Figure 2 framework. Figure 4 captures the uncertainty of the risk analysis across a range of different infrastructure provisions.



**Figure 4. Plot of risks in £ million vs. hazard exceedance probabilities. The solid line shows the mean risk and the shaded boundaries show the maximum and minimum risk outcomes.**

### Acknowledgements

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# Technological Vulnerability: Parameters And Definitions

L J Robertson<sup>a\*</sup>

**Abstract:** In the field of infrastructure security, there is significant definitional diversity of terms such as “vulnerable”, “resilient”, and even “risk”. Without clear definitions any derived metric will be similarly imprecise, and without metrics we can neither assess “vulnerability”, nor evaluate options for improvement. While research has made advances in metrics applied to homogeneous systems, adequate modelling of inhomogeneous (more than one service transmitted) and interconnected infrastructures (that supply goods and services to end-users), is generally regarded as being computationally intractable. This paper specifically considers the possibility of characterising end-user “exposure” of a complex technological system, and developing a metric for “exposure” that would allow evaluation of options for improvement in end-user security.

## I. Introduction

The Merriam Webster dictionary defines *Vulnerable* as “...1: capable of being physically or emotionally wounded 2: open to attack or damage: assailable ...”

It is perhaps a sign of increased dependence upon technology that the term “vulnerability” has migrated from this original context to the realm of complex technological systems. Certainly, “vulnerability” is a term increasingly associated with technological systems for delivering goods and services, and with the closely related topic of critical infrastructure security<sup>1,2</sup>. Within both of these contexts, individuals have become progressively more aware of the long and interdependent (technology) supply chains that provide our most basic needs.

Many options exist for decreasing the vulnerability (“hardening”) of existing infrastructural services, though in some cases one might suspect that these efforts offer little incremental value. In other cases, technology options for provision of end-user services exist, and may be preferable to risk reduction efforts addressed to existing technologies. There is pressure to identify the most cost-effective approaches, but lack of clarity of definitions hamper efforts to properly prioritise and evaluate options for infrastructural improvement. Definitions that are clear and consistent across a wide range of fields, would allow efforts to secure reliable services to be prioritised better, and would allow overall gains to be more readily demonstrated.

The Merriam Webster dictionary definition of vulnerability has been quoted previously. Birkman<sup>3</sup> states that “...the different definitions and approaches show it is not clear just what “vulnerability” stands for as a scientific concept... We are still dealing with a paradox: we aim to measure vulnerability, yet we cannot define it precisely... Although there is no universal definition of vulnerability...” Birkman also cites “...Strategy for Disaster Reduction (UN/ISDR), which defines vulnerability as: The conditions determined by physical, social,

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<sup>a</sup> PhD student, University of Wollongong.  
[lindsay@tech-vantage.com](mailto:lindsay@tech-vantage.com)  
<http://dx.doi.org/10.14453/isngi2013.proc.67>

*economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR, 2004)...”<sup>3</sup>. Einarsson and Rausand<sup>4</sup> write “...[t]he vulnerability concept has yet not been given a generally accepted definition for technological applications...”. Werbeloff and Brown<sup>5</sup>, go further by stating that “...[t]he concept of 'vulnerability' is a dynamic concept and as such is difficult to define...”. Baldick *et al.*,<sup>6</sup> in reflecting on power systems, declare that at the present time, there “...is not a commonly accepted vulnerability index or assessment method...”. Agarwal and England<sup>7</sup> agree that even within the (mature) structural engineering discipline, there is “...no satisfactory measure of robustness: not even a widely agreed definition...”*

This conference topic envisages complex, and inter-related infrastructures; It may be assumed that the topic of interest is not primarily homogeneous systems (in which a single service is routed through a network, and nodes simply aggregate or distribute that service) but rather inhomogeneous technological systems in which nodes require a variety of inputs to function, and where different parts of the technological system transfer different goods/services. Definitional difficulties cause some specific issues in the field of critical infrastructure and associated technological system.

## **II. Difficulties associated with terminology and definitions**

### **A. Risk and harm**

Different definitions of “Harm” will generate different assessments: quite minor “harm” to a sewage system might leave an apartment dweller without usable accommodation. By contrast, quite severe “harm” to a local road system might have limited effect on end-users if power and sewage are available, and supermarkets are close. Rigorous indexation of “harm” to the end-user, would offer a consistent definition of “harm”.

In regard to definitions of “risk”, ISO 31000 defines “risk” as “...effect of uncertainty on objectives...”<sup>10,11</sup> - such a definition is hardly precise or exclusive!

Posner<sup>8</sup> has attempted to consider events characterized by large harm and low probability. Others have considered events that are simply low probability (“black swans”)<sup>8</sup>. Within less extreme examples, many who practice in the field of risk management have noted that assessments based on a product of harm-probability and harm-magnitude, generates similar metrics for high-impact low probability, and low-impact high probability events.

### **B. 2.2 Vulnerability**

“Vulnerability” can be considered in terms of relationship between operational system load and design maximum system load, however that approach has limited application. This paper proposes that a refinement of the concept of “susceptibility to failure” offers a more useful definition, and the term “exposure” will be used for this refined definition of “vulnerability”.

## **III. “Exposure” of inhomogeneous technology systems**

### **A. Inhomogeneous technology system risks**

For homogeneous technological systems, graph theory offers some metrics to assess configuration and hence technological “vulnerability” (authors such as Idika & Bhargava<sup>9</sup>

review a number of metrics to describe the degree of interconnectedness of specific homogeneous networks). For inhomogeneous systems, by contrast, current thought is that complete modeling and characterisation is computationally impractical. Since the vast majority of technological systems are inhomogeneous, this is a significant gap.

Any measure of risk can only be associated with a specific technological system (a different technological system would have different values of risk) – yet when risk is quoted, it is rare to actually see inhomogeneous technological systems characterised in a way that quantitatively links it to the associated risks. If it were possible to characterise the configuration and components of inhomogeneous (infrastructural) systems, this would help in assessing their relative weakness level and the relative value (to the end-user) of “hardening” approaches.

### **B. Characterisation of inhomogeneous systems**

The previous section has converged on the issue of characterising inhomogeneous infrastructural systems, as a basis for improved assessment of alternative hardening approaches and targeting of efforts. This section proposes a general approach to the characterisation of inhomogeneous critical infrastructural systems, leading to a method of defining relative exposure to risk. The proposed approach assumes that it is possible to represent inhomogeneous infrastructural systems as set of interconnected unit operations, each needing a complete set of inputs in order to generate a design output.

### **C. Inverting the risk issue - hazards and exposures**

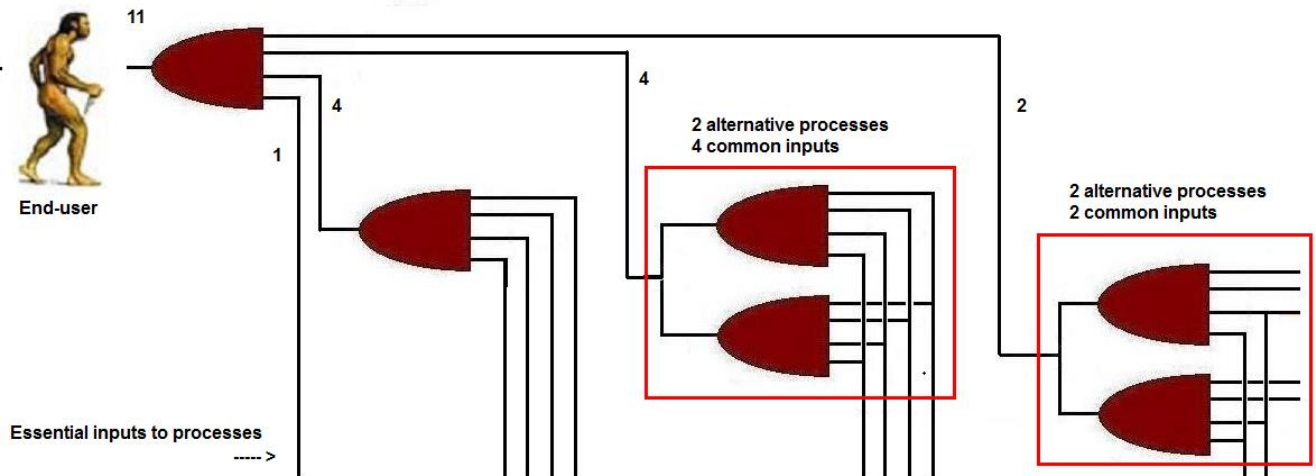
Risk assessments generally start with hazard identification, and proceed to assess the magnitude of harm, the probability of the hazard occurring, the likelihood that the identified hazard will actually cause the harm and the nature and effectiveness of any mitigation measures. This approach does not generate a good measure of the “vulnerability” of a technological system, nor a metric that can be readily used to evaluate alternative improvement options. It is proposed that a different approach is possible and useful.

A very fundamental, though seldom articulated truth is that a hazard is not a hazard unless it aligns with a system weakness. Therefore, regardless of the statistical probability of any specific hazard occurring (and such probabilities will tend to 1.0 over a long-enough period) occurring, the number of weaknesses will indicate the relative vulnerability/exposure of a specific technological system.

### **D. Quantifying the weaknesses of a technological system**

If the (inhomogeneous) technical system is represented in terms of a set of interconnected unit operations, each of which functions when, and only when all inputs are present (and which finally delivers the designated goods/services), then the quantum of input streams crossing the system boundaries has coincidentally defined the points of weakness. This is illustrated in the Figure 1.





**Figure 28. Weaknesses in processes leading to delivery of goods/services.**

Some clarifications and enhancements of this concept are needed, but an inversion of viewpoint is being proposed: instead of listing/evaluating threats/hazards, it is proposed to examine the number of hazard-targets (weaknesses).

For quantitative assessment, it is proposed to refer to the “exposure” of the technological system – the number of hazard-targets. However simple, a metric that assesses the number of points of weakness of a technological system offers some real utility: it is possible to compare technological systems and determine which has more “exposure”, and it is possible to evaluate a proposed change (configuration or components) to an inhomogeneous system and obtain a metric for the decrease in “exposure”. Considered in simplistic terms, it is proposed that an inhomogeneous technological system can be represented as a set of AND-gate/unit operations, each assumed to generate an output if, and only if, all inputs are present. For such a representation, each input (crossing the system boundary) represents a stream without which the output will fail – and so the sum of all inputs (to the sum of all unit operations), represents the number of weaknesses of the technological system and offers a measure of that system’s “exposure”.

In order to be useful, this basic definition needs to be refined and several obvious issues need to be addressed.

### **E. Refining the concept of "exposure"**

The proposed “AND gate” concept is simply a notional/logical and-gate, producing an output when all inputs exist. Inputs will include process streams, but in addition, one input to the “gate” is ALWAYS the functional unit operation itself (in an “operational” timeframe).

It is likely that there will be cases where an output stream could be alternatively sourced from more than one process. If all of the alternative processes that can generate a specified output are considered within a "bubble", it can be appreciated that the output stream is only jeopardised when inputs streams that are common to all the (alternative) processes are jeopardised. The "exposure" of the alternatively-sourced output is therefore related to the number of common inputs to all of the alternative processes.

In a real inhomogeneous system, there will be hazards that have a higher statistical probability of occurring within a given timeframe, and there will also be hazards with a lower

probability. Nevertheless, it can be observed that over a sufficiently long time period, all probabilities approach 1.0, and so a characterisation of the number of weak points remains a valid and useful metric.

In a real inhomogeneous system, many intermediate streams have some buffering capability. Such capability reduces the impact of very short-duration outages, and in a dynamic simulation of a specific system the interactions of demand variation and buffering capacities is of the essence. Nevertheless, few situations exist where long term buffering is possible, and for very many situations (e.g. electric power required to operate a motor) buffering is not available at all.

A metric for “exposure” would be impractical if the approach generated an unbounded scope. Initial work indicates that end points (where multiple alternatives exist, with no common inputs) are practical.

## **IV. Conclusion**

### **A. Significance of technology configuration**

This paper has commenced with a very high level review of definitions: it has proposed the consistent indexation of “harm” to end users, and has noted the need to develop a refined definition of the concept of “vulnerability” for inhomogeneous technological systems.

### **B. Technology system exposure**

The paper has proposed an approach for characterising a complex technological system; this approach generates a metric that represents the total “exposure” (to hazards) of the technological system. This provides a quantifiable refinement of the general concept of “vulnerability”, and unlike “risk” approaches, it not only recognises the significance of the underlying technological system but generates a metric closely linked to the actual weaknesses of a technological system.

### **C. Application**

As professionals considering the next generation of infrastructures, we note that

- Our infrastructural systems have tended to grow progressively larger and more complex, and to present more and more points of weakness.
- It is important to avoid expending much effort on “hardening” one system while failing to recognise that another system is inherently more vulnerable.
- It is important to avoid prioritising effort on one approach to “hardening”, without realizing that other approaches might generate a better outcome.

This paper proposes a simple method that characterises a technological system by assessing the technological weaknesses, offers a useful approach to both prioritisation of “hardening” efforts, and to reducing end-user exposure to failure.

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# Identifying Extreme Risks in Critical Infrastructure Interdependencies

K. Tai<sup>a\*</sup>  
A. Kizhakkedath<sup>a</sup>  
J. Lin<sup>a</sup>  
R.L.K. Tiong<sup>b</sup>  
M.S. Sim<sup>c</sup>

**Abstract:** Critical infrastructures like our power generation facilities and water supply form highly interconnected networks that are mutually dependent and any failure can cascade through the network, resulting in devastating impact on health, safety and the economy. These catastrophic events/disruptions can be triggered by environmental accidents, geological/weather phenomena, disease pandemics, etc. The disruptions can be caused/exacerbated by their being unexpected, but they may actually be expected if relevant data have been accounted for. To help account for and thereby anticipate such disruptions, one way is to identify potential unforeseen interdependencies among infrastructure components that can lead to extreme disruptions upon some failure in the network. This paper shows how a simulation model for cascading failures and a risk analysis/optimization approach can be applied to search for unforeseen interdependencies and failure points that give rise to the highest risk in a network.

**Key words :** Unforeseen interdependencies; Vulnerabilities; Risk analysis; Network analysis; Multi-objective optimization

## I. Introduction

Critical infrastructure refers to the assets, systems and networks comprising identifiable industries, institutions and distribution capabilities that provide a reliable flow of goods and services essential to the functioning of the economy, the government at various levels, and society as a whole<sup>1</sup>. Examples of critical infrastructure include facilities for energy/power generation, water supply, telecommunications, transportation, banking/financial services, security and health services, etc.<sup>2</sup>. They are highly interconnected and mutually dependent in complex ways, and the sudden unavailability of any of them or part thereof may cause loss of life, severe impact on health, safety or the economy<sup>3,4,5</sup>. The 9/11 terrorist attacks, the Indian Ocean tsunami of December 2004, the Hurricane Katrina devastation of the US Gulf Coast in 2005, the 2008 Global Financial Crisis, the 2011 Tohoku earthquake/tsunami and the severe flooding in Thailand late 2011 can be considered examples of such major disruptions/disasters.

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<sup>a</sup> School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

<sup>b</sup> School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

<sup>c</sup> Information Division, DSO National Laboratories, Singapore

\*Corresponding author: K. Tai ([mktai@ntu.edu.sg](mailto:mktai@ntu.edu.sg))

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Within a single sector of critical infrastructure (e.g. the electric grid), as well as among various mixed-type or multiple-sector infrastructure (e.g. electric grid and water supply), the interdependencies among their various components can be highly complex and can be quantitative or qualitative in character. Compounding the challenge of analyzing these interrelationships is that access to the required information is difficult because a vast majority of infrastructure assets are owned by the private sector and there are significant barriers to sharing information between the private sector and the government<sup>3</sup>. Furthermore, while experts within a particular infrastructure sector may be able to identify the interdependencies within that sector to build a concise network model for analysis, it is a challenge to identify the interdependencies between different sectors. Interdependencies are most often classified into the following five types<sup>6,7</sup>:

- Physical - A physical or engineering reliance between infrastructures, e.g. material flow from one infrastructure to another.
- Information/Cyber - An informational or control requirement between infrastructures, e.g. a reliance on information transfer between infrastructures.
- Geospatial/Geographical - A relationship that exists entirely because of the proximity of infrastructures, e.g. a local environmental event affects components across multiple infrastructures due to physical proximity.
- Policy/Procedural - An interdependency that exists due to policy or procedure that relates a state or event change in one infrastructure sector to a subsequent effect on another sector, e.g. government's emergency mandatory orders on a particular area due to the influence of an event.
- Societal/Logical - An interdependency that an infrastructure event may have on societal factors, e.g. public opinion, public confidence, fear, and culture issues.

The challenging problem of modelling the relationship/network models of these complex systems have motivated much research<sup>8,9</sup>. However, even if accurate models were built, it is unclear if the far-reaching consequences of the 9/11 terrorist attacks or the 2011 Tohoku earthquake/tsunami could have been anticipated. Very often, some interdependencies are explicitly revealed only after the disasters or disruptions occur. For example, the Tohoku disaster left over twenty thousand confirmed dead, injured or missing, and millions more affected by lack of electricity, water and transportation<sup>10</sup>. Extensive agriculture landscape was flooded, train stations and railway network were damaged, a dam failed in operation, fire occurred at an oil refinery plant, electricity transmission lines, ship and crane, highway bridges were damaged, and a level-7 nuclear accident happened at the Fukushima nuclear power plant<sup>11</sup>. Also affected were the interrelated supply chain business networks between Japan and other countries. To cooperate with electricity conservation efforts, many factories producing high technology components stopped production lines to support blackout measures.

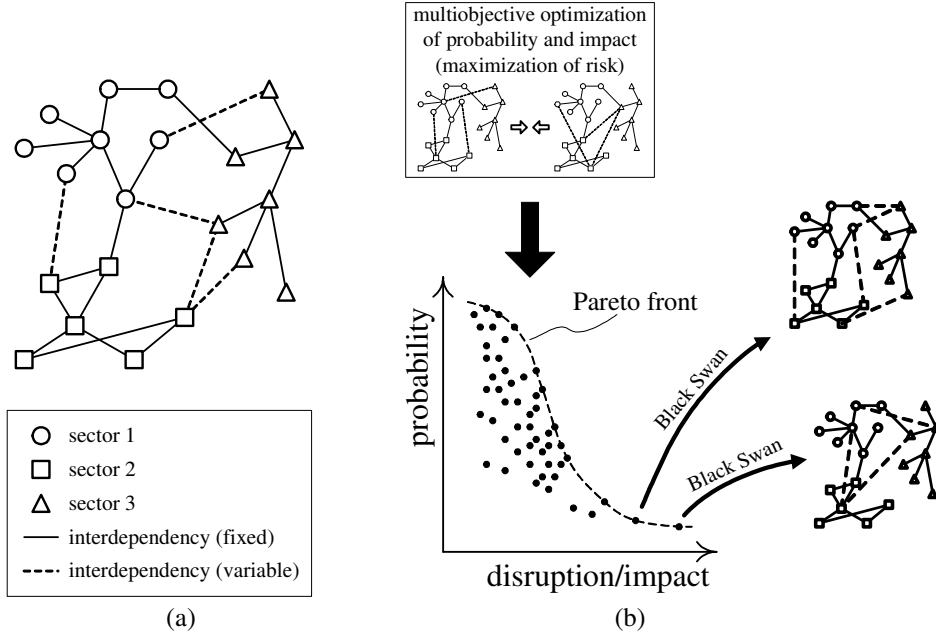
The idea that such high impact but highly unexpected events could actually have been expected if the relevant available data had been accounted for was put forth by Taleb<sup>12</sup> in his book "The Black Swan". Black Swan events are highly improbable events (outliers), and highly impactful, and can be caused and exacerbated by their being unexpected. However, in spite of being highly unexpected, it is natural that experts (and even casual observers) will retrospectively be able to construct explanations for their occurrence after they have occurred, making them explainable and expected. In the context of critical infrastructure, this is similar to the interdependencies that are explicitly revealed only after major disruptions.

As an example used by Taleb, the 9/11 attacks was an event that was a surprise to many observers with major impact/effects felt up to today on the heightened level of security and pre-emptive strikes against various parties. It is doubtful if any amount of modelling and analysis could have predicted how terrorist attacks on some commercial infrastructure could have led to the consequential shutdown of air-space, disruption of air travel around the world and the ensuing conflicts. It seems to imply how little our understanding of the complex systems in our society and physical world can help us guess what is going to happen next, and this Black Swan logic actually makes what we don't know far more relevant than what we do know.

Since it is a challenge to construct an accurate model of the network of critical infrastructure interdependencies/relationships and, anyway, our current limited awareness of the relationships may not be helpful to predict the highly improbable and high impact disruptions, it may be futile to go on to perform the required analyses on such models to predict the effects of those major disruptions. Hence, instead of analyzing a given infrastructure network to determine the effects of any failure, the overall aim should perhaps be to solve the inverse problem, i.e. to synthesize the network that will result in the most extreme disruptions due to some failure. This can be achieved by beginning with the set of infrastructure components, their known interdependencies and prescribed initial/boundary conditions and failure modes, and then apply optimization techniques to iteratively vary/modify the network with additional (unforeseen) interdependencies until the disruption effects are maximized. In this way, what is obtained will be a set of network models (with their associated interdependencies) that can potentially be realized in our real world and that will result in the most severe disruption effects due to various failures with associated probabilities. The resulting networks obtained can then be reviewed by a diverse team of experts to interpret the unforeseen interdependencies and potential scenarios that may lead to the realization of the disruptions computed for the network. As both the severity/impact of the disruptions and the probabilities of occurrence will both be computed as the criteria for the optimization, this represents a risk analysis approach of describing the problem and also a multiobjective optimization problem. Based on these ideas, this paper presents one way to investigate how the highly unexpected major disruptions (the Black Swan events) in our critical infrastructure systems can be anticipated by solving the inverse (optimization) problem of synthesizing infrastructure network interdependency models for extreme failure impact and probabilities. By investigating how the inverse problem can be formulated, the study in turn also explores the bounds (limits) of these extreme (catastrophic) disruptions that can arise from the interdependencies inherent in our critical infrastructures.

## **II. Optimization and Analysis of Infrastructure Network Disruptions**

The network model of critical infrastructures comprises the infrastructure assets/components (nodes) and the links representing their interdependencies, as illustrated in Figure 1(a) (for only three infrastructure sectors).



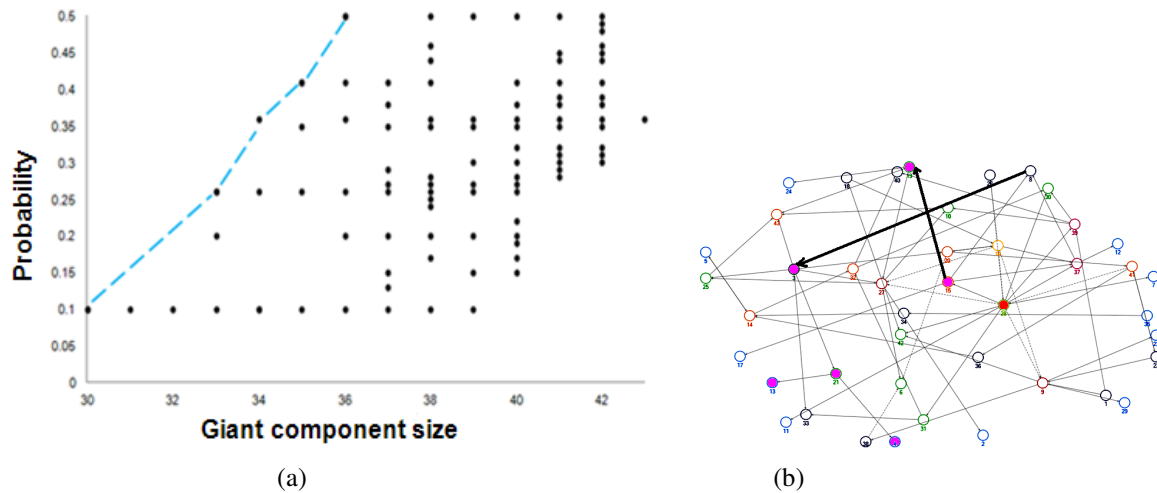
**Figure 1. (a) Critical infrastructure network model (b) Pareto optimal solutions of the multiobjective evolutionary optimization problem, with network solutions of extreme disruption representing Black Swan events.**

The study of the critical infrastructure vulnerabilities is based on a risk analysis framework, where risk can be defined as  $\text{risk} = f(\text{probability}, \text{impact})$ , i.e. as a function of the probability of a failure/hazard/threat resulting in an adverse event and the severity/impact of that event<sup>13,14,15,16</sup>. In the context of our problem, impact refers to the magnitude of the disruption in the network computed according to various metrics used in network theory such as, e.g. the giant component size<sup>17,18</sup>, using agent-based simulation<sup>19,20,21,22</sup>. Probability refers to the probability of the failures propagating/leading to the disruption. The optimization problem is therefore a problem of searching for networks and failures that maximize the two objectives of probability and disruption, with the decision variables being the unforeseen (variable) interdependencies and failure points within the network. With two objectives, an evolutionary algorithm<sup>23,24</sup> is used to iterate a population of solutions (i.e. a set of networks with corresponding failures) converging towards Pareto-optimality. In this way, optimization has been used to synthesize networks with the highest risk, while those with the extreme disruption impact can be considered the Black Swan events, as summarized in Figure 1(b).

### III. Results from Experimental Case Study

The proposed methodology was applied to an experimental case study with a network comprising 43 nodes with two variable (unforeseen) interdependencies added to the fixed (known) interdependencies. The results show that unforeseen interdependencies can indeed exacerbate the disruption consequences/impact, where impact is quantified by the giant component size (the smaller the size, the greater the impact). The plot in Figure 2(a) shows the optimal solution points obtained, with a line drawn through the Pareto-optimal solutions to represent the Pareto-front. The point at the lower extreme left is the Pareto-optimal solution with the greatest disruption (giant component size of 0.1), hence it can be interpreted as a Black Swan event, and it represents the scenario where failure occurs at node 30 and

where there are two unforeseen interdependencies as shown by the thick black lines added to the network in Figure 2(b).



**Figure 2. (a) Pareto-front of the multiobjective optimization of probability and disruption impact (giant component size) (b) Network with two unforeseen interdependencies added.**

#### IV. Concluding Remarks

By assuming that a significant part of the network interdependencies is in fact unknown (unforeseen), the proposed approach applies optimization to search for unknown interdependencies and failure points that will cause extreme events, thus leading analysts on a focused exploration of ‘what-if’ scenarios of high disruptive impact. In addition, it provides policymakers with a way to analyse the ‘trade-off’ between the high-probability/low-impact and the low-probability/high-impact events.

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## Biofuel Energy Production as Catalyst for Sustainable Agriculture in Nigeria

Luke Onyekakeyah<sup>a\*</sup>

**Abstract:** Two factors underlie the quest for biofuel energy production in Nigeria. First is the availability of vast arable agricultural land that is lying waste and largely uncultivated. The oil boom of the mid 70s upturned the country's economy from being predominantly agrarian economy to crude oil based diseconomy. The result is the shift to oil as a major source of foreign revenue. Consequently, the share of agricultural production in total exports plummeted from over 70 per cent in 1960 to less than 2 per cent today. The abandonment of agriculture has disorientated the economy, which is far from being developed. Second is the energy crisis that hit the economy due to the mismanagement of the crude oil revenue earnings and lack of appropriate energy policy framework. The collapse of the electricity sub-sector and the prohibitive price of petrol and other domestic cooking gas and kerosene forced the authorities to seek alternative sources of cheap fuel. The result was the decision by government to give impetus to biofuel production as one alternative energy source. The development of biofuel would inevitably boost agricultural production of the main cash crops needed as raw materials in industrial biofuel production. How to rekindle interest in agriculture has for decades remained a daunting problem to government. The objective of this paper is to review the policy framework and actions already put forward for biofuel production and assess the implications of such developments on agricultural production. This is with a view to ascertaining to what extent the introduction of biofuel into the energy mix would help to revamp the dwindled agricultural economy. In making this assessment, we sought and obtained relevant information from published materials relating to the issue of concern. These were analyzed in the light of the prevailing circumstances in the country's agricultural sector. Based on the information gathered and analyzed, we found out that embarking on biofuel as a source of energy would not only rekindle interest in farming but would boost commercial agricultural production of a variety of crops. Essentially, biofuel energy has the capacity to catalyze renewed interest in sustainable agriculture in the country. The study is significant as a source of information for policy makers in planning future line of action pertaining to sustainable agriculture. It is also useful to prospective local and foreign investors in commercial agriculture and biofuel production to counter balance the opportunities and choices available to them.

**Key words:** Energy; Biofuel; Sustainable agriculture; Nigeria

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<sup>a</sup> The Guardian Editorial Board Rutam House, Isolo, PMB 1217, Oshodi Lagos, Nigeria

\*Corresponding author: Luke Onyekakeyah lonyekakeyah@yahoo.com  
<http://dx.doi.org/10.14453/isngi2013.proc.34>

## **I. Introduction**

Geographically, Nigeria is located in tropical West Africa approximately between latitudes  $5^{\circ}$  to  $15^{\circ}$  N and longitudes  $3^{\circ}$  to  $14^{\circ}$  E. It is the third largest country in Africa after Sudan and Democratic Republic Congo, with a total land area of  $923,768 \text{ km}^2$ . The country shares borders in the east with Cameroon, in the west with Benin Republic, in the north with the Sahara Desert and in the south with the Gulf of Guinea part of the Atlantic Ocean with which it shares 853 km coastline. In terms of population, Nigeria is the most populous country in Africa and the eight most populous countries in the world with an estimated population of 148 million, according to the 2007 United Nations projections. Economically, Nigeria is a major producer of crude oil. The country is a prominent member of the Organization of Petroleum Exporting Countries (OPEC). She is the largest crude oil producer in Africa and the 6<sup>th</sup> among the OPEC countries and the 8<sup>th</sup> largest exporter in the world<sup>1</sup>. Petroleum plays a critical role in the country's economy. Since the dawn of oil boom in the mid 1970s, oil has dominated the entire economic system. About 90 per cent of the country's foreign revenue is derived from crude oil export.

Notwithstanding that the price of oil has soared in the world market over the past three decades with Nigeria earning huge revenue now put at over \$400 billion since 1960, the country's economy still remains among the least developed in the world. The country scored 0.470 (low) in the 2007 Human Development Index and was placed at the 158<sup>th</sup> position in the world. According to the Economist Intelligent Unit and the World Bank, Nigeria's Gross Domestic Product (GDP) at purchasing power parity was only \$170.7 billion in 2005. The GDP per capita is \$692<sup>2</sup>. The poor state of affairs has been attributed to high-level corruption and mismanagement of the country's resources. Unfortunately, this has impacted negatively on practically every sector of the economy. Among other things, Nigeria suffers from severe and chronic energy crisis that has crippled the economy and left the country literally in darkness. Agriculture was abandoned in preference to oil. This has turned the country into a net importer of food while its vast arable land is lying waste.

## **II. Agriculture Potential**

Nigeria has great potentials for agricultural development. Over 90 per cent of the country's landmass is arable and could support a wide variety of agricultural products. It is estimated that 82 million hectares out of the country's total land area of about 91 million hectares, or 90 per cent are arable. Unfortunately, only about 34 million hectares, or 41 per cent are under cultivation mostly by peasant farmers. The remaining 48 million hectares of arable land or 59 per cent are lying waste and uncultivated. The climate and soil are conducive for the cultivation of a wide range of crops such as cassava, maize, millet and sorghum. The Food and Agriculture Organization (FAO) classifies the country's soil to have medium to high productivity if properly managed. Peasant farmers cultivate crops in smallholdings using crude implements. The output is grossly low and insufficient for the country's food requirements.

Prior to the oil boom that occurred in the mid 1970s, the country's economy was predominantly agrarian with over 60 per cent of the workforce engaged in peasant farming. Major cash crops such as palm oil, cocoa, rubber, cotton, groundnuts and timber were produced for export. Agriculture was the main foreign exchange earner accounting for over 70 per cent in total exports. The shift to oil diseconomy however overturned the agrarian

economy and has ever since impacted negatively on agricultural production. Today, the share of agricultural production to total exports has plummeted to mere 2 per cent! Since the 1980s, the growth in agricultural output has not been impressive. For instance, in the first half of the 1980s, which was a period of stagnation in the country, the growth in output averaged just about 0.5 per cent. This was attributed to low producer prices, marketing restrictions and drought. Many farmers abandoned their farm plots in pursuit of other viable economic activities. Some took up white-collar jobs in the cities. Shortly, afterwards, there was a slight improvement in the fortunes of agriculture following some economic reforms introduced in 1986. These included improved producer prices, trade liberalization, dissolution of price fixing marketing boards and the devaluation of the naira.

As a consequence, growth in the sector rose slightly and averaged 3.8 per cent. Many farmers returned to their abandoned fields and there was a burst of activity in cash crop production. The renewed interest however was not sustained. There was little investment in cash crop production, instead, more food crop was produced which contributed to a drastic fall in food importation from 19.3 per cent of total imports in 1983 to 7.1 per cent in 1991. The government has made effort through giving incentives to encourage farmers to invest in agriculture and agro-based industries but this has not been successful. For instance, the production of cocoa, which is the country's biggest non-oil foreign exchange earner, has remained stagnant at around 160,000 tons per year since 1995. In comparison, the annual average production of cocoa before the oil boom was more than 400,000 tons. The same goes with the other cash crops. The challenge facing the government is in revamping agricultural production and ensuring its sustainability. There is need to shift from subsistence farming to large-scale mechanized agriculture. It is on this basis that we consider investment in large-scale cash crop production for biofuel energy production as important in the quest to revive agriculture.

### **III. Energy Crisis**

Nigeria is currently facing a crippling energy crisis. The energy supply is grossly insufficient to meet demand. As a result, the entire country is literally plunged into darkness. This has impacted negatively on socio-economic development goals. The energy output in the country is put at a meager 4000 megawatts (MW) or 4.7 per cent. This amount is generated from all power sources currently in operation. It is generally believed that for the country to grow industrially, the energy generated should be in the neighborhood of 30,000 MW. There is a large gap when this amount is put against what is currently produced.

Nigeria has a wide range of potentially exploitable energy sources. These include hydropower, coal, gas, solar and wind energy. There is also plan to explore nuclear and biofuel energy alternatives. So far, the entire energy need of the country has concentrated on hydropower and gas while the others are left untapped. Unfortunately, both the hydropower and gas have been poorly harnessed. The irrational and lopsided attention given to hydropower and gas are the reasons why the other available sources of energy are not put into the energy plan.

At independence in 1960, there were two electricity-generating bodies in the country. These were the Electricity Corporation of Nigeria (ECN) and the Niger Dams Authority (NDA). The two organizations showed great prospects in generating electricity at a time when the economy was predominantly agrarian with low industrial output. In 1972, the two

electricity organizations were merged and the National Electric Power Authority (NEPA) was created. Throughout the period, NEPA's performance was anything but good. There was constant epileptic power supply throughout the country, which slowed down economic growth. Many industries folded up due to unreliable power supply. The disgust over NEPA's poor performance reached a crescendo as the economy literally ran on private generating sets that flooded the country. Consequently, in 2006, NEPA was scraped and renamed the Power Holding Company of Nigeria (PHCN), with 18 business units in its stead. The country has a total installed power generating capacity of about 5,000 MW comprising of both hydro and thermal power plants. The 8 main electricity-generating stations in the country are presented in Table 1.

Owing to official negligence and lack of maintenance, most of the generating plants depreciated and could hardly generate a quarter of their installed capacity. Many packed up and went out of service. In the circumstance, there was need for a total refurbishment to put the plants back on line. This imperative forced government to embark on a rehabilitation plan of some of the ailing power plants as a way of boosting energy output. This involved the replacement and refurbishment of transmission lines and transformers. Between 1999 and 2008 about N7.5 billion (\$62,500,000), contract was awarded for the rehabilitation of the 3 units of the Egbin Power Plant of which two of the units, ST4 and ST6 were out of service since 1992. It was planned that the rehabilitation would add at least 660 MW to the 1320 MW plant. Meanwhile, another contract was awarded for the rehabilitation of the premier Kainji Dam. The work involved the complete dismantling of the 8 units of the power plant. It is remarkable that power output in this and the other two dams is affected during the dry season due to low water level. Furthermore, government devised the National Independent Power Plants (NIPP), under which it proposed to build a number of gas-powered stations in different parts of the country. Table 2 presents the proposed independent power projects.

Some state governments also embarked on the development of power plants. The Lagos State Government, for instance, entered into an agreement with Enron Corp of America to build a gas-powered station. The Lagos/Enron power project added 60 megawatts of electricity to the national grid. The Rivers State Government has also completed its own independent power plant. The other states are at various stages of negotiation with their foreign partners to build state owned power plants. It is remarkable that despite this entire attempt, the power sector remains prostrate. The country spent a whopping N16 billion (\$135.5 million) on the power sector in eight years without any visible change or improvement. The crisis in the energy sector provided a fertile ground for graft.

Allegations of corruption, embezzlement and mismanagement of funds have trailed the award of the power contracts by the administration of former president Olusegun Obasanjo. Consequently, the National Assembly decided to probe the entire contracts that were awarded under the independent power projects. Until the issues are sorted out, the Nigerian power sector provides an attraction for prospective foreign investors to take advantage of the huge market that is untapped over the years.

**Table 1: Electricity Generating Stations in Nigeria**

Name	Location	Type	Capacity (MW)	Installation date
Ijora	Lagos State	Thermal	60	1956
Kainji	Niger State	Hydropower	760	1968

Ogorode	Lagos State	Thermal	60	1978
Jebba	Kwara State	Hydropower	540	1985
Egbin	Lagos State	Thermal	1320	1987
Shiroro	Niger State	Hydropower	600	1990
Delta VI	Delta State	Thermal	600	1991
Afam	Rivers State	Thermal	NA	NA

**Table 2: Proposed National Independent Power Plants (NIPP)**

Name	Location	Type	Capacity (MW)
Geregu	Kogi State	Thermal	414
Omotosho	Ondo State	-do-	335
Paplanto	Ogun State	-do-	335
Alaoji	Abia State	-do-	346
Gbarian	Bayelsa State	-do-	225
Ihovbor	Edo State	-do-	451
Egbema	Imo State	-do-	338
Calabar	Cross River State	-do-	561
Ibom	Akwa Ibom	-do-	188

#### **IV. Biofuel Energy Option**

The slow pace of action in realizing the goal of boosting power supply through the independent power plants and the uncertainty surrounding the energy sector formed the basis for looking beyond hydropower and gas for alternative sources of energy. One energy source that is being explored in this regard is biofuel.

Notwithstanding the criticisms against diverting agricultural land to biofuel crop production, government is in the process of developing a framework that would encourage the development of this form of cheap energy to augment what is available. The argument that the development of biofuel would put food out of the reach of the poor is out of the question in Nigeria. While this may be true in some land hungry countries, this is not the case with Nigeria where 48 million hectares or nearly 60 per cent of the country's arable land is lying waste. Nigeria has enough land to grow food crops as well as industrial raw materials for biofuel production. For instance, under the post-independent agrarian economy, large tracts of land were held for the cultivation of export cash crops such a palm oil, cocoa, rubber, timber and cotton without reducing food crop production capacity.

Today, with the abandonment of agriculture, most of the tracts of land used for cash crop production are lying waste. The land is neither used for the production of crops for food nor for industrial raw materials. In the circumstance, it therefore makes more economic sense for the country to put the land into crop cultivation for biofuel. Nigerians are desirous of having cheap energy supply irrespective of the source. There is therefore no discontent from the people on the development of biofuel technology in the country. Government on its own is gradually bracing up with the idea of developing biofuel energy technology to reduce the country's energy crisis. In what follows, we shall highlight some of the policy initiatives and actions taken so far by both the government and the private sector towards the development of biofuel in Nigeria.

## **V. Policy initiatives and actions**

The Federal Government of Nigeria is currently fashioning out a new energy policy. In June 2007, government approved and issued a gazette on a National Biofuel Policy Incentive (NBPI), which provides the enabling environment for investors to operate. Subsequently, the Nigerian National Petroleum Corporation (NNPC) created a Renewable Energy Division (RED) upon the mandate of government to spearhead the development of the biofuel industry in the country. RED has launched the biofuel initiative by inviting Expressions of Interest (EoI) to enlist core joint-venture (JVs) investors into the industry. The joint venture projects will include investment in large-scale cultivation of sugarcane, cassava ethanol and palm oil biodiesel production. Phase one of the programme includes the launch of four large-scale agricultural ventures as follows:

- A 2x20, 000 hectares sugarcane plantations, fitted with an ethanol, sugar and cogeneration plant.
- A 1x10, 000 hectares cassava farm fitted with an ethanol plant.
- A 1x20, 000 hectares palm oil plantation fitted with oil extraction and biodiesel conversion plant.

The NNPC has accordingly secured appropriate contiguous locations for the projects in parts of the country and has initiated detailed feasibility studies with reputable international experts. The Corporation is seeking to create under the JVs strategic investors with recognized operational expertise in managing the various crops and plants envisaged in the programme. The modalities for the operation and management of the projects are being worked out for the take off of the projects. The Jigawa ethanol project is another programme that government initiated to produce ethanol from sugarcane. These projects are still at the initial stages of completion. They will go into full-scale operation as soon as government works out detailed modalities with its joint venture investors.

A consortium of research organizations, companies and civil society organizations recently announced that it would establish an “AgroTown” (“Biofuel Town”) in Nigeria to kick-start a biofuel revolution on the continent. The project which is to be located near Lagos is directly supported by the governments of Brazil and Nigeria. Brazil’s President Lula da Silva is a staunch advocate of using biofuel as a vehicle for international cooperation and development assistance. The phase one of the “Biofuel Town” project will comprise of a settlement that would house 1000 bioenergy experts in an area of 6 million square meters. The project is expected to cost US\$100 million.

## **VI. Private Sector Intervention**

Global Biofuels Limited, a private venture concern has initiated the construction of Nigeria’s first biofuel refinery at Arigidi-Akoko in Ondo State. The refinery is expected to begin operation in July 2009 with a daily production capacity of about 1.5 million liters of ethanol. The plant is reported to have the capacity to employ no fewer than 58, 000 people. Out of this, 8, 000 would gain direct employment, while 50, 000 would be engaged indirectly in the project. The plant would also help Nigeria achieve the mandatory E-10 requirement of the Kyoto Protocol. This requires signatory countries to introduce 10 per cent bio-ethanol with 90 per cent petrol into their market. Obviously, all the effort Nigeria is making is future-



oriented. By linking the agricultural sector to biofuel energy, the agricultural potentials of the country would be revolutionized.

## VII. Conclusion

The foregoing sections have highlighted some of the critical issues surrounding the introduction of biofuel into the energy mix in Nigeria. Biofuels are fast gaining credibility and acceptance in many countries particularly in the developed world. The production of biofuels as a substitute for oil and natural gas is actively being pursued by countries focusing on the utilization of cheap organic matter such as cellulose, agricultural and sewage wastes to produce efficiently liquid and gaseous biofuels that yield high heat energy. The only subsisting argument against biofuel production is the perceived diversion of agricultural land and the envisaged food crisis it might generate. Considering Nigeria's poor energy standing and low agricultural productivity, there is need for the country to diversify its energy potentials and invest in mechanized agriculture. Agriculture and biofuel are mutually inclusive and beneficial. Based on the foregoing, it is obvious that embarking on biofuel energy would rekindle interest in farming and boost commercial agriculture. That way, biofuel would have catalyzed sustainable agriculture in the country.

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# Pilot Application of the Infrastructure Sustainability Rating Tool to Council Road Management

R. Walters <sup>a\*</sup>

S. Lees <sup>b</sup>

**Abstract:** Sustainable development requires infrastructure to be durable, minimise reliance on non-renewable resources, provide maximum benefits to society and the environment and contribute to prosperity in the long term. ISCA developed its infrastructure sustainability (IS) rating tool to assess the sustainability of both new projects and the operation of existing assets. The tool drives improved sustainability performance of infrastructure across all infrastructure sectors and all stages of the infrastructure lifecycle. The tool was piloted extensively on new projects and is now being taken up enthusiastically by industry to rate sustainability performance. During piloting, the rating tool had only undergone limited trials on infrastructure operations so ISCA and IPWEA undertook a pilot trial on the road management activities of two local councils. This paper describes the outcomes of the trial, actions that can be taken to make road management more sustainable and the next steps to progress use of the tool.

**Key words:** Sustainability; Infrastructure; Rating; Councils; Roads; Asset management

## I. Introduction

Sustainable development requires infrastructure able to deliver sustainability outcomes. Infrastructure should be able to provide its intended services over its lifetime, efficiently and reliably, place minimum reliance on non-renewable resources, provide maximum benefits to society and the environment and contribute to, rather than endanger, national prosperity in the long term.

Roads are the largest assets class of many local types of council, with road management their largest operational activity. 84% (by length) of all of Australia's roads are maintained by Australia's 560 local councils with a value exceeding \$100 Billion.

The IS (Infrastructure Sustainability) Rating Tool was developed by the Infrastructure Sustainability Council of Australia (ISCA) to drive improvements in the lifecycle sustainability of Australia's infrastructure. Prior to this project the IS rating tool had only undergone limited trials on infrastructure operations, so ISCA was keen to see the tool further trialled on existing infrastructure assets.

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<sup>a</sup> Infrastructure Sustainability Council of Australia, Sydney, NSW, 2000, Australia.

<sup>b</sup> National Director Sustainability, Institute of Public Works Engineering Australia, Sydney, NSW, 2000, Australia.

\*Corresponding author: Richard Walters [rwalters@isca.org.au](mailto:rwalters@isca.org.au).  
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This project was a joint initiative of ISCA and the Institute of Public Works Engineering Australia (IPWEA), along with support of and participation by the several pilot councils and financial support from the Australian Centre of Excellence for Local Government (ACELG). Two councils were selected to pilot the tool – Redland City Council on Moreton Bay, southeast of Brisbane; and Launceston City Council in northern Tasmania. Confirmation trials are also being undertaken with Brisbane and Logan City Councils.

The project involved IPWEA and ISCA staff working alongside staff of two local councils to apply the rating tool and propose modifications to facilitate use of the rating tool for council road management.

The ultimate long-term goals are to:

- customise the IS rating tool so that it can be used to rate the operation and maintenance of existing infrastructure
- demonstrate the practicality and benefits of applying the customised rating tool to local council road management
- promote use of the rating tool by local councils to drive sustainability improvements in asset management.

The more immediate goals of this project were to:

- propose modifications to the IS rating tool so that it can be used to assess the sustainability performance of local council roads management.
- help the pilot councils assess the sustainability of their road management activities and identify ways these can be improved.
- draw general conclusions about the sustainability of local council road management, what councils can do to improve their sustainability performance and what IPWEA can do to support councils in that regard.
- make recommendations to ISCA about follow-on work in subsequent stages.

## **II. Sustainability Rating Schemes**

There is a global trend towards using rating schemes to drive improvements in sustainability, initially for buildings, but now for infrastructure. One of the first rating schemes for infrastructure was ‘CEEQUAL’ in the UK, which started in 2003 and has to date rated more than 150 infrastructure projects. More recent infrastructure rating schemes include the Institute for Sustainable Infrastructure’s ‘Envision’ in the US; ‘INVEST’ for highways, also in the US, and of course ISCA’s ‘IS’ Rating Tool in Australia.

## **III. IS rating scheme**

The IS rating scheme is Australia’s first and only national sustainability rating scheme for infrastructure. It is a voluntary scheme that aims to assess sustainability performance across the quadruple bottom line of economic, environment, social and governance criteria. The types of infrastructure covered by the rating scheme include transport, water, energy and communications. Key benefits of the IS rating scheme are:

- provides a common national language for sustainability in infrastructure.
- supports consistent application and evaluation of sustainability in tendering processes.
- scopes whole-of-life sustainability risks for projects and assets, enabling smarter solutions that reduce risks and costs.
- fosters resource efficiency and waste reduction, reducing costs.
- encourages innovation and continuous improvement.
- builds an organisation's credentials and reputation in its approach to sustainability in infrastructure.

The IS Rating Tool has six themes, 15 categories and 51 credits. ISCA also intends to develop additional 'Economic' and 'Workforce' themes in the future. The current themes and categories are shown in Table 1. The IS rating tool was developed between 2009 and 2011 and launched in February 2012. Since then the first new infrastructure projects are now (early to mid-2013) being subject to the formal rating process with the first two ratings certified in April and May 2013. Note however that until now the rating tool had only undergone limited trials to assess the sustainability performance of existing infrastructure operations.

The following section outlines general (nonformatting) guidelines to follow. These guidelines are applicable to all authors (except as noted), and include information on the policies and practices relevant to the publication of your manuscript.

Themes	Categories
Management & Governance	Management Systems. Procurement & Purchasing. Climate Change Adaptation.
Using Resources	Energy & Carbon. Water. Materials.
Emissions, Pollution & Waste	Discharges to Air, Land & Water. Land. Waste.
Ecology	Ecology.
People & Place	Community Health, Well-being & Safety. Heritage. Stakeholder Participation. Urban & Landscape Design.
Innovation	Innovation.

**Table 1. IS rating tool themes and categories.**

#### IV. Rating Assessments

The assessment process involves determining the most appropriate level for each credit and recording this in the rating tool scorecard. Credits may be 'scoped out' if they are not applicable. When all the credits have been assessed, the scores are weighted and summed to produce an overall score on a 100 point scale. In a formal assessment process ratings are certified to the following overall rating levels:

- Commended (score of 25-49).
- Excellent (50-74).
- Leading (75-100).

## **V. Rating Process**

The rating scheme currently offers three rating types:

- Design rating – at the end of its planning and design phase.
- As-built rating – at the end of its construction phase.
- Operation rating – after at least 24 months of operation, and then revalidated every five years.

The rating process can be undertaken formally or informally. The formal process involves the following steps:

- Registration
- Assessment
- Verification
- Certification

An informal rating process might typically only involve Assessment, with no ISCA input or guidance. An organization can use the results of an informal assessment internally to identify and implement sustainability improvements, but the rating results cannot be used publicly without the formal certification (including third party verification) from ISCA. The rating process for this project was informal.

## **VI. Methodology**

As outlined above, the project's Stage 1 methodology involved, broadly, applying the rating tool to assess the sustainability of the road management activities of the two 'pilot' local councils; proposing modifications to the rating tool to make it more suitable for that purpose and then drawing general and council-specific conclusions about how local councils can make their roads management more sustainable. Three assessment iterations were undertaken at each pilot council, with the rating tool revised and refined after each assessment. Subsequent confirmation assessments for two further councils were also undertaken.

## **VII. Scope**

The scope was called 'local road management' and defined as the operation (i.e. on-going management) by council of its current road network within the road corridor or reserve, excluding major road upgrades and construction. This scope of the ratings aimed to be broad enough to provide opportunities for local councils to enhance the sustainability of their road networks, but excluding major upgrades and new road construction projects as these works are generally large enough to warrant their own sustainability rating as new infrastructure projects (Table 2 with the excluded activities and tasks highlighted in grey).

The phrase 'road network within the road corridor or reserve' means that the scope includes all operational and maintenance activities listed in the AUS-SPEC TECHguide (NATSPEC 2013), which includes:

- pavement and shoulder repairs
- bridges, tunnels, culverts, drains
- gutters and kerbs
- footpaths, street furniture, bus shelters, street landscaping
- street lighting
- traffic control – signs, traffic lights, guard rails
- grass mowing, weed control and tree management in the road reserves
- litter, graffiti and stormwater pollution controls
- road reserve emergency and storm damage response.

### VIII. Pilot Rating Assessments

ISCA and IPWEA staff held kick-off workshops with each council in late January 2013 to resolve key issues, like boundaries and scope, but also to brief a wide range of council staff on the project and enlist the support of senior management. Each theme, category and credit in the rating tool was assessed in turn, and the scores recorded in the rating tool's scorecard. Some credits were identified as likely to be not applicable. For these pilot trials, those credits could either be scoped out (if not applicable for that council) or proposed to be permanently removed from the tool for operational rating of local roads (if deemed not applicable for all councils).

Activity	Task	When?	Betterment?	New Asset?
Operations	Operations	On-going	No	No
Maintenance	Maintenance	On-going	No	No
Renewal	Renewal	End of useful life	No	No
	Rehabilitation	End of useful life	Maybe	No
Upgrade	Minor upgrade	Any time	Yes	Partial
	Reconstruction	End of useful life	Yes	Partial
	Major upgrade	End of useful life	Yes	Yes
New construction	Construction	Any time	Yes	Yes

**Table 2. Council road management activities.**

After each assessment workshop IPWEA and ISCA resolved various issues and updated the rating tool with changes that had been proposed during the assessments. The updated tool was then used in the subsequent assessments. Further, but fewer, issues and changes were addressed and resolved after the second and third assessments (in March and April 2013 respectively).

### IX. Issues Raised

The pilot applications of the rating tool to the road management activities of the two councils raised a number of issues, both general and category or credit specific. The general issues identified included:

- interpretation was required to apply the rating tool benchmarks to the operations context given they had been trialled primarily on the design and construction of new infrastructure.

- the approach to comparing footprints to a baseline required a modified approach compared to that used for new infrastructure projects.

The issues specific to particular categories or credits included:

- the relevance of targets or requirements in the benchmarks for some credits that are not specific to road management.
- street lighting, which is typically the largest use of energy in roads management, is commonly paid for by local councils, but managed by energy distribution companies.
- the Was-3 credit that rewards actions to facilitate asset deconstruction/disassembly at the end of its life, is less meaningful for roads because they are almost always renewed indefinitely.

## **X. Proposed Modification to the IS Rating Tool**

Over the course of this project, modifications were proposed to the original rating tool specifically for rating the sustainability of local council roads management. The proposed modifications greatly simplify the tool, with the number of credits reduced from 51 to 35.

The other main changes made were to:

- remove credits that are not applicable to road management.
- combine several credits within a category into one, where appropriate.
- simplify targets and make them more roads-specific.
- broaden the disassembly credit to also reward minimizing rework by facilitating future upgrades.
- make consistent the requirements for the credits that rely upon changes in footprints (i.e. Energy, Water, Materials and Ecology).
- make the requirements for inspections and audits consistent.

The customised rating tool provides for the full range of activities within the adopted scope.

## **XI. Assessment Results**

Detailed advice will be provided to both pilot councils at the end of this project in a confidential briefing. The assessment identified a number of initial actions that local councils can implement to start to make their local roads management more sustainable. These early sustainability improvement actions include:

- ensure Council's Sustainability commitments are reflected in its sustainability targets, then in its contracts and procurement processes.
- ensure that a member of Council's senior management team is accountable for managing and regularly reporting on Council's sustainability performance, including that of its road management.
- explicitly consider sustainability criteria in goods and services procurement for road management.
- undertake an assessment of climate change risks to the roads network.

- monitor, compute and report on energy use and GHG emissions; potable and non-potable water usage; materials usage and waste quantities and types associated with roads management .
- investigate and identify all feasible and cost justifiable ways to reduce energy use and GHG emissions; potable and non-potable water usage; materials usage and waste.
- survey ecologically sensitive sites and heritage items along the road corridors and implement effective and appropriate measures to protect those sensitive sites and heritage items.
- regularly undertake an appropriate and risk-based program of community and user safety audits.
- engage with stakeholders (including the community) when preparing council's road assets management plan.
- implement a formal process for responding to and promptly resolving all community complaints about adverse impacts from roads management activities.
- develop comprehensive amenity and landscape management plans for the roads network, undertake roads management in accordance with those plans and regularly monitor for compliance.

The rating assessments scored both councils' road management activities at or below the Commended range (25-49). However readily-implementable actions, such as those listed above, were identified for both councils that, if carried out, would potentially increase their total scores into the Excellent range (50-74).

## **XII. Next Steps**

At the time of writing, the rating tool was being refined through confirmation assessments at two further councils. It is hoped that a customised rating tool can be made available to other local councils around Australia to assess and rate the sustainability of their roads management activities. Over time, with more widespread use, it is expected that the customised rating tool would be updated – especially the benchmarks – as what constitutes good sustainability practice becomes more clearly defined.

Furthermore, it is likely that with relatively minor further changes the tool could be customised to assess other types of local government assets with similar characteristics (e.g. stormwater/ drainage assets and open space, parks, garden and sporting fields).

## **XIII. Conclusions**

Trial applications of the original rating tool to assess the road management activities of two local councils in different areas of Australia identified proposed modifications to the tool to make it more suitable to rate the operational phase of that type of infrastructure asset.

Use of the customised rating tool to informally assess the road management activities of the two pilot councils demonstrated its practicality and benefits. The outcomes will help the councils to identify ways that their road management can be made more sustainable. The outcomes will also help IPWEA draw general conclusions about the sustainability of local council road management, what councils can do to improve their sustainability performance and how IPWEA can support councils in this regard.



#### **XIV. Recommendations**

Follow-on actions could include:

- reviewing how the customised rating tool might be made available for use, promoted and maintained.
- drafting extra Additional Guidance on the customised rating tool for the Technical Manual
- proposing fees for formal operational rating assessments by local councils.
- developing an economic theme, possibly incorporating the three financial sustainability indicators described in the IPWEA's Practice Note 6 (IPWEA 2012).
- developing an ongoing program with IPWEA to encourage use of the customised rating tool by local councils and its further refinement.
- investigating opportunities to further pilot and modify the rating tool to facilitate assessing the sustainability of local council management of other assets.

#### **Acknowledgements**

Financial support for this project was provided by the Australian Centre of Excellence for Local Government. That support is gratefully acknowledged. Special thanks are also given to staff of the two pilot councils, Redland City Council and Launceston City Council and also Brisbane and Logan City Councils.

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# Green Infrastructure: Connecting People with Landscapes through Urban Retrofitting

Marci Webster-Mannison<sup>a\*</sup>

Malcolm Eadie<sup>b</sup>

Sally Boer<sup>c</sup>

Peter Breen<sup>d</sup>

**Abstract:** This paper demonstrates a new way to integrate green infrastructure in the urban design of our cities whilst they continue to increase in density. A pilot study demonstrates how the population may be doubled through sensitive infill of the inner-city Brisbane neighbourhoods situated in the historical catchment of Western Creek. Hydrological modelling used MUSIC to size the associated green infrastructure elements and to quantify the benefits in terms of stormwater improvements. The Western Creek Pilot Study reveals the important role that multifunctional green infrastructure has to play in the development of local solutions to urban intensification in response and energy, land, food and water supply pressures as part of a climate change adaptation strategy.

**Key words:** Green Infrastructure; Urban Design; Retrofitting Cities; Climate Change Adaptation

## I. Introduction

The Green Infrastructure: Connecting people with landscapes through urban retrofitting research project, funded by the Australian Government's Department of Infrastructure and Transport, is about understanding how to integrate the urban design of cities with green infrastructure to meet the challenges of rapid urbanisation and uncertain future climate scenarios.

The project focus was on developing and evaluating new urban typologies for the Western Creek Pilot Study, located approximately three kilometres South-West of the Brisbane CBD in a 416 hectare catchment of the Brisbane River. This existing inner-city area is considered a high-density Urban Neighbourhood, however, currently the predominantly character housing area is low density (approximately 10 dwellings per hectare) with about approximately 11,500 residents, or 4,160 households. The planned population increases for the Western Creek neighbourhoods effectively double the existing density over the next twenty-five years.<sup>1,2</sup>

The Western Creek Pilot Study established the urban densification framework for the hydrological modelling of green infrastructure solutions including the following:

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<sup>a</sup> Centre for Sustainable Design, University of Queensland, St Lucia Queensland 4072, Australia.

<sup>b</sup> E2DESIGNLAB, Sunshine Coast Queensland 4567, Australia.

<sup>c</sup> E2DESIGNLAB, Brisbane Queensland 4101, Australia.

<sup>d</sup> E2DESIGNLAB, Melbourne Victoria 3000, Australia.

\*Corresponding author: Marci Webster-Mannison [m.webstermannison@uq.edu.au](mailto:m.webstermannison@uq.edu.au)  
<http://dx.doi.org/10.14453/isngi2013.proc.48>

- Viability of introducing green infrastructure related to permeability, land ownership and creation of important ecological links and urban design analysis.<sup>3,4</sup>
- Community Workshop.<sup>4</sup>
- Establishment of the site development potential to increase site density was identified on a site-by-site basis by the researcher, Marci Webster-Mannison and testing of density solutions across over 100 sites considering detailed factors by Masters of Architecture students.<sup>5,4</sup>

The green infrastructure solutions were generated through a research-by-design process which integrated the hydrological assessment and modelling of the catchment, development of options, various consultations and design charrettes using the Water ToolKit developed for the Western Creek Pilot Study by E2DESIGNLAB.<sup>5,4</sup>

## **II. Modelling**

Quantitative modelling was undertaken by E2Designlab to measure the potential benefits of green infrastructure solutions as part of urban densification of the Western Creek catchment in Brisbane. The modelling uses MUSIC Version 5.01 (Model for Urban Stormwater Improvement Conceptualisation, eWater) and Microsoft Excel to measure change from existing for un-mitigated and mitigated (using green infrastructure) urban intensification scenarios.

### **A. MS Excel water balance model**

A Microsoft excel water balance model was developed for the Western Creek catchment using existing and projected population and land use data for each Scenario and typical water end use data obtained from the literature, to generate annual water balances for potable water demand and use, recycled water demand and use, wastewater (grey and black) generation and re-use, and stormwater and rainwater (from roofs) generation and re-use.

### **B. MUSIC**

MUSIC Version 5 was used to model the quantity and quality of stormwater flows for the Western Creek Catchment. The model generates estimates of annual stormwater pollutant loads (kg/yr) and daily peak stormwater flows from which a partial series analysis was undertaken to generate estimates of peak flow for various Average Recurrence Intervals (ARIs).

## **III. Existing Scenario: Methods and Results**

### **A. Stormwater pollutant load and flows**

A MUSIC model, Scenario One\_ Existing Situation, was developed to represent the existing conditions in 7 sub-catchments of the Western Creek catchment (Figure 1). Existing land uses were consolidated into the following categories of Detached Residential, Multi-Residential, Commercial, Industrial and Open Space / Forested for ease of modelling using the MUSIC Modelling Guideline parameters. The outputs from MUSIC were then analysed to calculate peak flows using partial series analysis.

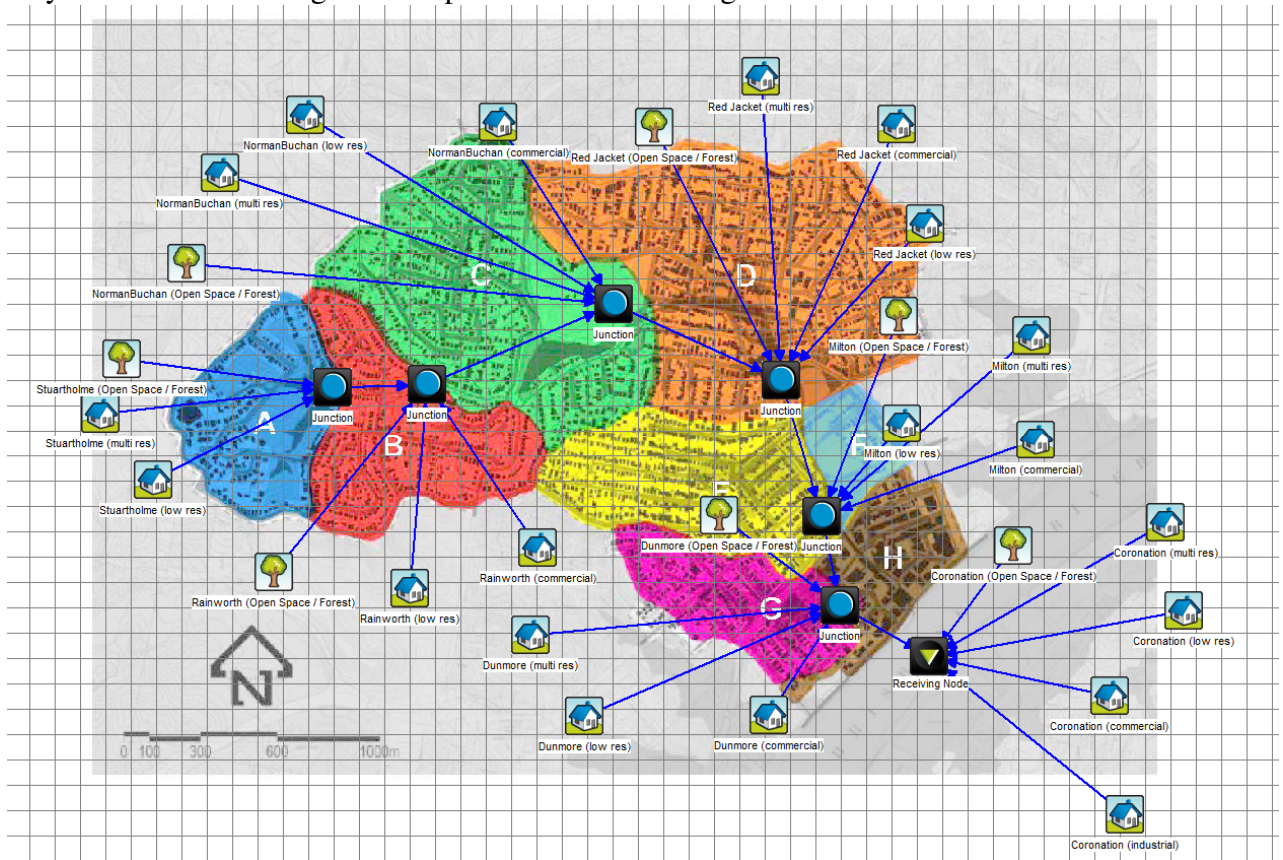
### **B. Water balance**

The existing water balance for the Western Creek catchment was determined using the total areas (ha) for commercial, low density residential and multi-density residential land uses, dwelling density (dwellings/ha) and dwelling occupancy rates and typical water

demands per/person. The results of the water balance analyses show that currently the largest water demands are generated in the low density detached residential land uses which is the dominant land use across the catchment.

Although all water demands in the catchment are currently serviced by the regional potable water supply, the results clearly show that a large portion of that demand could be serviced by alternative water sources such as roofwater, treated stormwater and treated wastewater on a 'fit for purpose' basis.

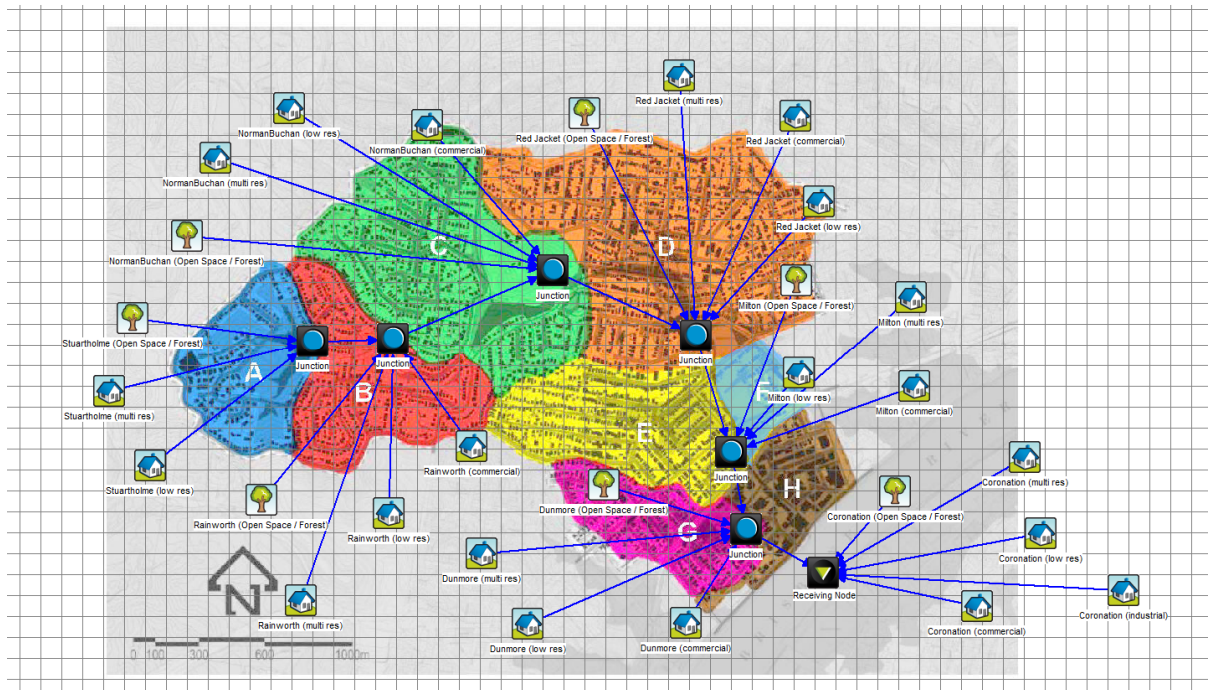
The significantly high proportion of recycled water demand in the commercial land use is due to toilet flushing being the predominant water demand in these buildings, which can be met using recycled water. The detached low density residential land use has a high proportion of recycled water demand when compared to the multi-density residential areas. Even though recycled water can be used to meet the toilet flushing and laundry demands across both of these residential land uses, the irrigation demand is higher for the detached low density areas due to the large landscaped areas on these larger lots.



**Figure 1. MUSIC model of Scenario One\_Existing Situation**

#### **IV. 'Un-Mitigated' Urban Intensification: Methods and Results**

A MUSIC model, Scenario Two\_Future Un-mitigated Urban Intensification, was developed to represent the future conditions of each sub-catchment assuming population densification without green infrastructure (Figure 2).



**Figure 2. MUSIC model of the future – unmitigated Western Creek Catchment**

### A. Stormwater pollutant load and flows

The majority of land use change planned for the Western Creek catchment is conversion of low density residential to medium density residential. The results show that there is a very minor impact on stormwater quality and hydrology (flow) between Scenario One\_ Existing Situation and Scenario Two\_Future Un-mitigated Urban Intensification Scenario due to the relatively minor change (increase) to the overall catchment imperviousness. The results indicate that there would be only a minor impact on local flooding and waterway health from the planned urban intensification. What the results mask however, is that catchment urbanisation to-date has already impacted significantly on flooding and waterway health in the catchment with resultant poor amenity, resilience and ecosystem services.

### B. Water balance

The results of the water balance analyses for existing and future show that there will be a decline in water demands and wastewater generation for commercial and low-density residential areas which can be explained by the reduction in these two land uses in the future scenario. The results show however, a significant increase in total water demand (currently met using 100% potable water) and wastewater generation associated with the increase in multi-density residential areas. The increase in water demand is largely driven by an increase in demands for uses which require potable water (e.g. bathroom and kitchens) associated with the increase in residents, thereby limiting any potential increase in the proportion of total water demand which could be met with the use of recycled water. Compounding this issue is the reduction in irrigation demand due to the conversion of large landscaped detached house lots to medium density residential developments with limited irrigation demand, and the conversion of landscaped areas to hardstand roofs and paving, also resulting in an increase in roof runoff and stormwater runoff.

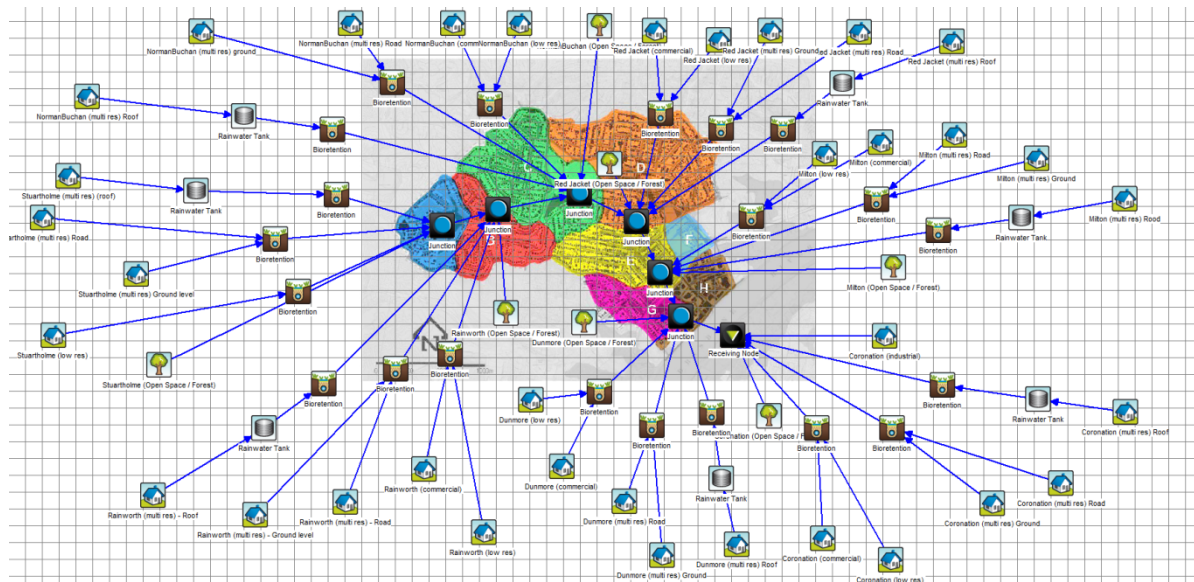
## V. 'Mitigated' Urban Intensification: Methods and Results



Scenario Two\_Future Un-mitigated Urban Intensification MUSIC model was modified to represent same level of population densification with the addition of Green Infrastructure to create Scenario Three\_ Mitigated Urban Intensification (Figure 3).

Green Infrastructure measures included the following:

- Provision of rainwater tanks for all new multi-density residential developments connected to internal uses (toilets and laundry cold tap) and for external uses (landscape irrigation) to reduce potable water use.
- Provision of 'extra-over' capacity in rainwater tanks installed in all new multi-density residential developments to minimise downstream flash flood risks.
- Pipe drainage disconnection for roads and other surfaces (roofs and ground level areas) from downstream waterways using on-site and streetscape bioretention to treat residential and commercial areas to protect downstream waterway corridors.
- Provision of an alternative water source (recycled wastewater) for the commercial area in the downstream section of the catchment to reduce potable water use and minimise wastewater production.



**Figure 3. MUSIC model of the future Western Creek Catchment with Green Infrastructure**

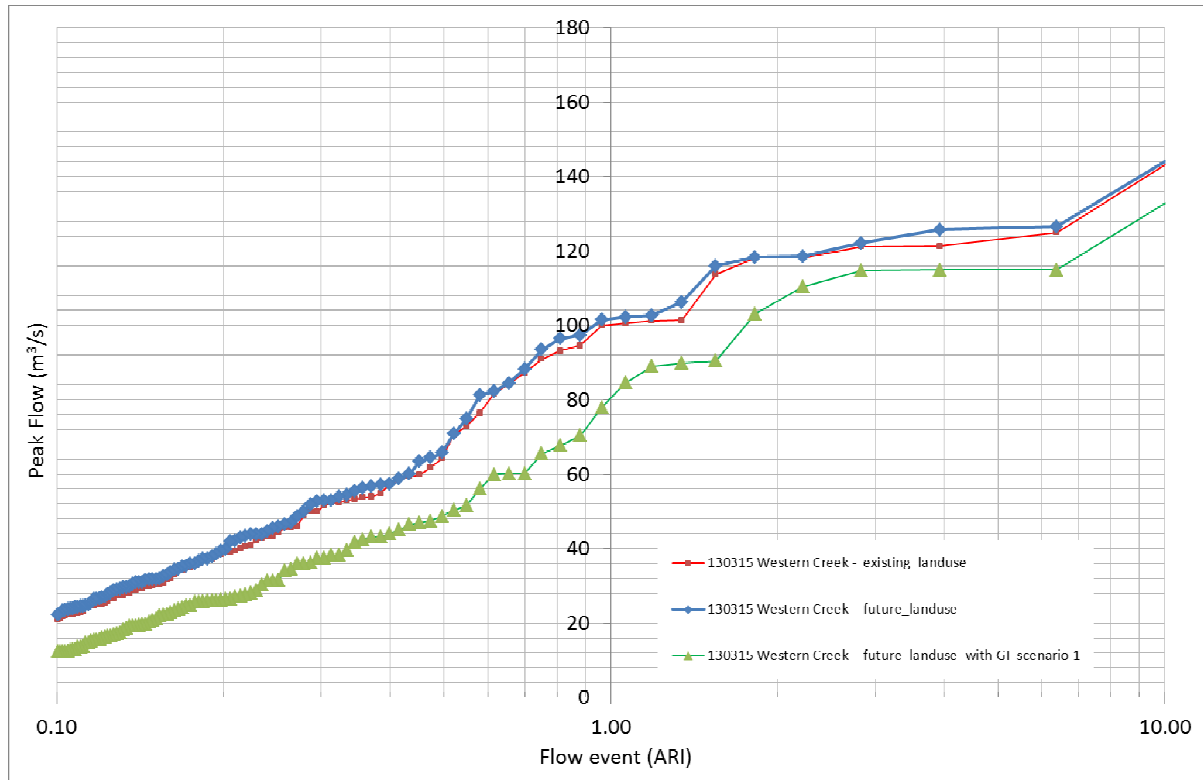
### A. Stormwater pollutant load and flows

The partial series analysis results show that green infrastructure can have a significant improvement on stormwater quality and peak flows compared to the existing catchment condition (Figure 4). This highlights that incorporating simple, well understood and tested green infrastructure solutions as part of urban renewal/re-development can allow for urban intensification whilst significantly improving the functionality and amenity of the catchment. Benefits include:

- Reducing hydraulic and water quality pressures on existing waterways assets in the catchment and downstream of the catchment thereby improving their resilience to

future extremes and shocks and allowing for higher levels of ecological recovery (remediation).

- Reducing the hydraulic loading on existing aging stormwater drainage infrastructure thereby extending its useful service life.
- Reducing the frequency of nuisance type flooding and associated disruptions to the functionality of the catchment.



**Figure 4. Partial series analysis outputs showing reduction in peak flows associated with inclusion of green infrastructure**

## B. Water balance

The Future Water Balance Model was modified to reflect the use of rainwater tanks to meet recycled water demands for new multi-density residential areas and on-site blackwater treatment and re-use to meet recycled water demands for commercial areas. The average annual 'yield' (ML/yr) from installation of rainwater tanks in medium density residential areas was measured using the MUSIC model (100% of the recycled water demand for commercial land uses was assumed to be serviced from on-site blackwater treatment and re-use). The results show that the use of rainwater tanks for all medium density residential developments and the treatment and re-use of blackwater in the commercial land use areas can reduce the volume of potable water used by the catchment to less than existing. Therefore, the use of green infrastructure can be used to successfully achieve population densification in catchments while reducing the overall demand on regional potable water supplies and infrastructure. Furthermore, the reduced discharge of roofwater and blackwater from the catchment (compared to the existing situation), reduces downstream ecological and infrastructure impacts and costs.

The combination of rainwater tanks on medium density residences and blackwater recycling in commercial areas is able to meet only 60% of the total recycled water demands

across the catchment. Therefore, further reductions in the catchment's demand of the regional potable water supply could be achieved by exploring the feasibility of additional recycled water sources, for example, stormwater harvesting and sewer mining. The feasibility of these recycled water sources are highly site specific and although beyond the scope of the current project, further highlight the need for an integrated site-specific approach at the building, lot, street, sub-catchment and catchment scale.

## VI. Conclusion

This modelling has highlighted the multi-functional nature of the benefits that green infrastructure can provide when implemented as part of an urban retrofitting and densification. In older urban catchments where natural and built assets are already under-pressure, green infrastructure solutions enable population increases whilst reducing the pressure on existing infrastructure assets. The benefits are multi-functional and resilient with improved amenity and lower overall costs associated with population growth due to avoided and/or delayed trunk water services infrastructure augmentation.

Notable results from the modelling are:

- The inclusion of rainwater tanks in new multi-density residential developments with a provision for extra-over capacity for flood attenuation can reduce (compared to existing) peak stormwater flows at the catchment outlet by up to 30% for more frequent events;
- Implementing on-site and streetscape bioretention to treat stormwater runoff from new multi-density residential and new commercial areas can provide significant water quality benefits for downstream waterways (between 40% and 70% reductions in annual pollutant loads compared to existing);
- Provision of alternative water sources (i.e. recycled wastewater for the new commercial areas and rainwater for new multi-density residential) can reduce the catchment's demand on regional potable water supply by 30% compared to existing.

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# **Zooma – A feasible pathway for Australia’s next infrastructure paradigm**

Trevor Chorvat<sup>a\*</sup>

**Abstract:** There are many paradigms that could shape this century’s infrastructure in Australia, and indeed the world. The suggested pathway – called Zooma – uses a fully automated passenger and freight system (Gazelle) leveraged by a consumer- and business-accessible built-in logistics system (the Super Postal Service). Gazelle uses light small vehicles moving inside an elevated track way. Contact-less propulsion, levitation and switching ensure reliable and efficient operation. Gazelle is self-sufficient in renewable energy. In contrast to linear arterial modes of transport, Gazelle uses a parallel distributed network transport paradigm to increase volume. Zooma’s real-time and predictive costing data facilitates a transport futures market which also helps to reduce congestion and optimises infrastructure utilisation. Zooma provides independent mobility and is a viable choice for people wanting a carbon free alternative to the car without having to forego the convenience of modern life.

**Key words – sustainable, smart, transformation, transport infrastructure, renewable energy, congestion, commuting, transport market, automation, integration, innovation, land use planning**

## **I. Introduction**

Transport depends on one factor that influences the delivery of nearly all human needs – energy. Meeting basic human needs of growing populations in a cohesive social, healthy environmental and sustainable economic context continues to challenge governments around the world. Within this context, shifting energy and transport strategies at the margin have limits to delivering net benefits under prolonged population pressure. In the end, paradigm shifts – a fundamental shift in individual and society’s view of how things work in the world – have to be made in order to ensure desirable social, environmental and economic outcomes. Such shifts are an imperative to creative metropolitan land use planning strategies that lead to reduced conflict involved with urban consolidation and renewal.

New transport infrastructure is now recognised as a pathway to paradigm shifts in land-use planning philosophies. Nine key thematic paradigm shifts in energy and transport that are either currently underway or that could possibly be delivered in the future are presented below.

### **1. Energy sources from non-renewable to renewable,**

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<sup>a</sup> Independent Researcher, Wollongong, NSW, 2519, Australia,( [tc@genling.com](mailto:tc@genling.com))

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2. Fossil-fuel use from extensive to zero,
3. Mode track system capacity in heavy usage times spread from concentrated linear routing to distributed parallel routing,
4. Origin-destination access of shared transport for passenger and for freight from area-to-area to point-to-point,
5. Shared use of transport vehicles from limited to extensive,
6. Digital integration into transport from limited to deep,
7. Vehicle control from manual to automated,
8. Use of transport-dedicated people time from high to low, and
9. Land dedicated to transport use from high to low.

While converting cars to use electric sources of energy may go some way towards delivering renewable energy (theme 1) and fossil-free fuel (theme 2), electric vehicles are unable to deliver on system capacity limits (theme 3). As population pressures increase, more people time is devoted to transport and more resources are allocated to trimming travel time and costs because of congestion. In response, urban dwellers seek shared use of transport vehicles via taxis or public transport. However, these options are either expensive or deliver only area-based origin-to-destination capability (theme 4). Consequently, system networks (theme 3) never shift from concentrated linear routing to distributed parallel routing, which would deliver latent system capacity and reduce congestion in peak periods. Further, shared use of transport vehicles (theme 5) faces difficulty in shifting from limited to extensive. Electric cars (and their variants) will therefore not lead to a paradigm shift in transport. Driver-less cars seem promising. However, the increasingly critical themes of people-time and land-use are missed, and the efficiencies arising from distributed parallel routing are mostly foregone.

A true paradigm shift in transport will only occur when digital integration of transport becomes deep (theme 6) and when fully automated transport becomes available (theme 7). Certainly, GPS, smart devices, telematics systems, timing, alert systems and logistics included in courier and freight tracking systems are assisting existing transport modes to offer a range of new customer value propositions<sup>xxvi</sup>. However, these smart systems are hosted on existing transport modes with their attendant track system capacity and origin-to-destination capability characteristics. Driverless cars take the smart use of cars to their logical conclusion<sup>xxvii</sup>. However, the form of the car limits its automation capability and its use in the same space as pedestrians will remain a significant practical problem. Accordingly, only a new mode with the capability to deliver themes 1 to 7 will lead to a true paradigm shift in transport. Such a new mode would engender business innovation and transform customer and household engagement and resource usage<sup>xxviii</sup>. With economic transformation, improvements in transport-dedicated people time (theme 8) by congestion reduction can be made to enhance city liveability. Further, reduction in land required for transport (theme 9) would provide for a robust metropolitan land use planning strategy platform<sup>xxix</sup>. The new transport mode is called Gazelle with a customer interface called the Super Postal Service. Together, these two elements form the Zooma paradigm.

The objective of this paper is to show that the proposed solution – Zooma – is a feasible paradigm-shift pathway and warrants funding to a stage where Zooma can be examined on its merits in any global city’s metropolitan urban transport and land use planning strategy. The key elements of the Zooma vision are introduced in the next section. The new automated transport mode called Gazelle is described in Section 3. The Super Postal Service that co-ordinates Gazelle’s new functionality and makes the new logistics functions accessible is outlined in Section 4. Section 5 explains how Zooma transforms transport so that it adds a new element to the converging technologies, creating an ITCT paradigm where Information Technology (IT), Communications (C) and Transport (T) are all integrated. Section 6 briefly describes how the Zooma paradigm addresses the Factor 8 challenge<sup>xxx</sup>. Section 7 examines whether Zooma is a feasible value proposition along technical, sensory, peak-period operations, pricing and economic dimensions. The final section provides summary and conclusions.

## II. The Zooma Vision

The key elements of the Zooma paradigm are presented in Figure 1. Gazelle is a new transport mode; its goal is to provide fully automated transport. Customers use computing and telecommunications systems to interact with the Super Postal Service to send people, postal items and freight to desired locations in the Gazelle network. Customers interact in a similar way that they would with email software, except that physical objects are sent rather than text, pictures and file attachments. Since Gazelle effectively makes transport digital, the Super Postal Service is able to host with other business-to-business systems and transport futures markets. Deep integration of an automated transport mode and its spin-offs would lead to transformation in many economies and address much of the Factor 8 Challenge. More detail on the Zooma concept may be found in Chorvat and Brama (2013)<sup>xxxi</sup>.

**Figure 1 Key features of Zooma**

Gazelle	Super Postal Service	Transformative Transport	Addressing the Factor 8 Challenge
<ul style="list-style-type: none"> <li>• Fully automated mode</li> <li>• Plats (very light vehicles)</li> <li>• Air cushion levitation</li> <li>• Linear motor propulsion</li> <li>• Contactless switching</li> <li>• Self sufficient in renewable energy</li> <li>• One month energy storage</li> <li>• Elevated enclosed tracks</li> <li>• Access points every 60 metres</li> <li>• High volume</li> <li>• Medium load</li> <li>• Point to point</li> <li>• On demand</li> <li>• Dynamic, globally optimised routing</li> <li>• Fine mesh network</li> </ul>	<ul style="list-style-type: none"> <li>• Allows customers to interact with Gazelle via email-type software</li> <li>• Smart phone SPS transport apps</li> <li>• Each Gazelle access point is a Micro-Post Office</li> <li>• Sends people as well as postal items &amp; freight</li> <li>• Efficient small items transport</li> <li>• Auto-'carpooling' commuting</li> <li>• Dynamic pricing</li> <li>• Range of send options</li> <li>• Care &amp; supervision</li> </ul>	<ul style="list-style-type: none"> <li>• Paradigm shifts: from concentrated to distributed; from linear to mesh; from hierarchical to uniform; from private to public</li> <li>• Intensifies Just-In-Time logistics</li> <li>• Convergence of Transport into Information Technology &amp; Communications: ITCT</li> <li>• Efficient transport market &amp; pricing</li> <li>• True and full costing of transport</li> <li>• Allows business to reshape customer value propositions</li> </ul>	<ul style="list-style-type: none"> <li>• Decouples economy from carbon production</li> <li>• New transport infrastructure capacity that augments existing infrastructure</li> <li>• Frees up land previously dedicated to transport</li> <li>• Returns city to people</li> <li>• Congestion gone</li> <li>• Air pollution gone</li> <li>• Scarce resources used most efficiently</li> <li>• Facilitates increased housing densities</li> <li>• Creative metropolitan transport and landuse planning strategies</li> </ul>

### III. Gazelle

The Gazelle transport mode aims to provide fully automated transport of people and goods within a city using a fine-grained mesh network. With this capability Gazelle could replace all cars, taxis, buses, light truck and palletised goods haulage within the city. However, Gazelle could not replace (non-palletised) heavy road transport. Gazelle articulates very well with other modes of transport. In particular, the train system would be able to leverage this articulation capability and gain efficiencies.

Gazelle uses an elevated and enclosed track to give it the security and exclusive right of way required for a safe fully automated system. The track enclosure has continuous windows along each side so that passengers can see out. The Gazelle track enclosure is 2.8 metres (9 feet) in diameter. Nominal track elevation would be 2.3 metres (7.5 feet), sufficient for uninhibited pedestrian and cyclist access under the track. Any road vehicle able to park undercover at a shopping mall or multi-storey car park can move or park under the Gazelle track.

The Gazelle track is single lane and one way. There are no intersections – only splits and merges. The tracks run down the centre of every street and minor road. Gazelle tracks also run down either side of heavy road transport corridors. That way, the current operations of important corridors are retained. It is possible for the direction of Gazelle track to be changed in response to general traffic flow.

Gazelle vehicles travel along the track and are called ‘plats’. Plats are payload platforms and take the form of flat bases. Plats can carry a variety of freight types, or if seats are installed, passengers. Plats are enclosed in a clear aerodynamic shroud in order to minimise drag, as well as allowing passengers to see outside. Plats and their payloads are propelled by a linear electric motor. The weight of the plat and payload is supported by an air cushion. Standard plat speed is 102 kilometres per hour (64 miles per hour).

Payload cross-sectional envelope is 2 metres high by 2 metres wide (6 foot by 6 foot). Payload length can extend to 6.5 metres (21 feet). Payload weight can vary from 760 kilograms to 1,500 kilograms (1670 - 3300 pounds) depending on length of plat. Plats are lightweight, so there is a high payload to weight ratio – an order of magnitude better than for cars.

Access points for the mode are ubiquitous and are positioned every 60 metres (200 feet) along the track, with 6.5 metre (21 feet) roll-on-roll-off access points every kilometre. Getting the payload to and from ground level is achieved by rapid lifts. Business truck loading bays are replaced by Gazelle auto-ports that can automatically dispatch or receive freight. Small, light, short-haul electric vehicles purpose-built for their accessibility and utility provide mobility for loads beyond the Gazelle track. Such light electric vehicles can be used for domestic trades purposes. The Gazelle track transports the electric vehicles over distance and provides recharging facilities for them, so they need only carry minimal battery weight and need only be designed to withstand crash tests for speeds at or below 40 kilometres per hour (25 miles per hour).

The roof of the Gazelle track is covered with photovoltaic panels, which provide the electrical energy to operate the entire system. Integrated electric storage units provide sufficient storage capacity for 25 days ‘sunless’ operation, with total recharge in 10 days

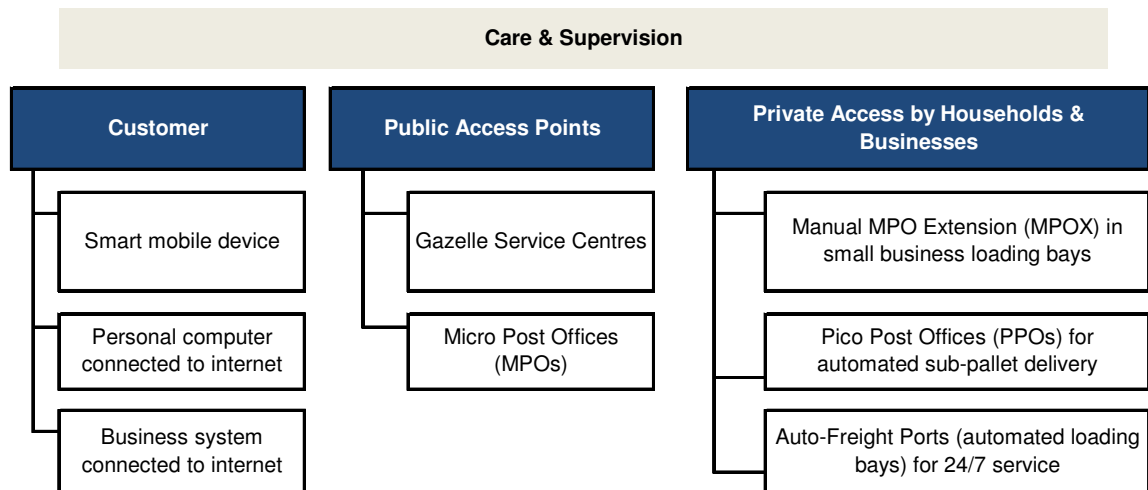
(based on an example using Sydney, Australia, which has average daily operations supporting 23 million passenger trips and 50 million tonne-kilometres of freight per workday<sup>xxxii</sup>). The track includes its own electricity distribution network. The electricity storage and distribution capability of Gazelle can serve as a ‘renewable energy infrastructure’ – facilitating the more widespread use of renewable energy sources.

The Gazelle network is controlled by computers. The speed and routing of every plat is controlled entirely through the track. There is no on-board power or control requirement. Globally optimised routing avoids congestion and flexibly re-routes plats around any track unavailability. While plats are driverless, they are not unsupervised. The Super Postal Service provides integrated payload supervision and care.

#### IV. Super Postal Service

Figure 2 displays the key components of the Super Postal Service. A postal service is an organisation that provides guaranteed levels of care and delivery of mail and parcels at an economical cost. The service takes responsibility for transporting your goods safely. You can send and forget, assured that your parcel or letter will arrive safely and timely at its destination. A super postal service extends this to provide for sending both people and freight. The idea is that you can ‘post’ yourself to work or you can ‘post’ your child to ballet lessons. In contrast, the current practice is to use a manual personal transport system composed of taxis or cars.

**Figure 2 Key Features of the Super Postal Service**



Customers access Gazelle and the Super Postal Service via their smart mobile device, personal computer or internet-connected business systems. Essential to the Super Postal Service is its attribute of ‘being everywhere’ or its ubiquity. The Super Postal Service leverages the ubiquity of the Gazelle access points: post boxes in a range of sizes form a micro-post-office in the wall of one end of each access point. Such ubiquity locates a micro-post-office within 30 metres (100 feet) of all residential homes, and at the doorstep and loading bay of every business. The Super Postal Service is transparent – driven by the automation and control within Gazelle systems. A transport customer can see the status of all packages (goods or people) sent, received, and in-transit via their hand-held electronic device. The transport customer is notified when any of the packages change status. And so

transport customers are always in the loop, fully informed at all times, in control of what happens to packages and where they go. Importantly, the Super Postal Service supplies a digital platform to enable economic transformation using a transport mode.

## **V. Transformative Transport**

The cornerstone of current transport systems is the fixed and linear system within a grid or radial framework. Such systems foster congestion because users are forced to congregate on major thoroughfares. In these days of online navigation systems real-time information about delays on the current route are available, but of limited use as alternate routing options are difficult to reach since travel through back streets is – rightly – discouraged. In contrast, Zooma offers a distributed parallel transport network where real-time supply and demand information is used to route traffic across the network more evenly. With more efficient use of network capacity, travel times are reduced and more equitably spread among Zooma users.

Transformative transport comes about as Zooma integrates with systems used by households, businesses and government to deliver smart transport. Such integration will leverage off Gazelle's automation and the Super Postal Service's accessible functionality to co-ordinate the logistic functions. While Zooma initially adds to existing transport infrastructure capacity, as business practices change to integrate Gazelle and the Super Postal Service more fully into an economy, Zooma will replace existing transport modes and transform the transport market.

Fully automated transport would add value to transport. Computer systems that control the low level movement of goods and people can be designed to also provide high level, integrated functionality into business, or Business-to-Business Transport, and Just-in-Time Transport and Built-in Logistics. Using Zooma, transport services become very similar to a telecommunications utility in terms of forward bookings, level of service, dynamic pricing, billing and so on. For example, Zooma enables businesses to have on-demand transport in the form of plats (rather than a fleet of taxis or light taxi trucks). Manufacturers would no longer need to wait until sufficient produce is accumulated for a whole truckload before dispatching. Retailers are supplied goods sooner. A more direct producer-consumer relationship is fostered.

A well-functioning transport futures market would develop because a reference computer system has information about future network usage via the Super Postal Service. The Super Postal Service also provides easy access to the market for users. Moreover, the interaction of users supplying data on their people and product space requirements together with timing, sources and destinations establishes the framework on which user charges would be set consistently across an entire Zooma network, and provide incentive for Zooma users to make the most cost-efficient choices. A transport futures market avoids congestion before it happens, rationing overall use of the available capacity of the Zooma network in the most efficient way. Customers are rewarded for their advance notifications with cheaper transport.

Zooma transport infrastructure therefore has many channels through which economic transformation can occur in order to address the Factor 8 challenge.

## **VI. Addressing the Factor 8 challenge**

*“Given that infrastructure is not an ‘engineering artefact’ but an ‘agent of change’, is it possible to imagine infrastructure systems that can meet the needs of twice today’s population with half today’s resources while providing twice the liveability? (Factor 8)”*  
— University of Wollongong<sup>xxxiii</sup>

The Zooma paradigm delivers positive associations for supporting **double the population** through lower energy use, lower transport costs, lower supply-chain and end-point food wastage, reduced competition by bio-fuels and fossil-fuel extraction (such as Coal Seam Gas) on agricultural land and water resources and reduced physical footprint on landscape by the transport system (less disruptive to habitat and agriculture). Competition for land within cities from the transport and logistics services would be significantly reduced. Energy security would be enhanced.

Zooma assists in **halving the resource footprint** by supercharging the utility and effectiveness of co-operative consumption. Zooma facilitates a market for recycling, repurposing and re-use by making resource movement easier and cheaper from someone who doesn’t want it to someone who does. Zooma is long-lived, ethically-used, ethically-sourced infrastructure with a life span of over 50 years. Zooma would assist in driving transport fossil fuel usage to zero and preserving limited fossil fuel resources for the more valuable and more sustainable petrochemicals industry.

The Zooma paradigm enables positive connections for **doubling the liveability** in cities via several channels including elimination of congestion and pollution, green space enhancement, health and safety improvement, transport accident minimisation and active lifestyle facilitation. Zooma could improve mental health by reducing commuter issues, road rage, road accidents, public transport overcrowding, sirens at night, road noise and stress for pedestrians and cyclists. Connecting isolated elderly and disabled people improves their quality of life and general health and wellbeing.

## VII. A Feasible Pathway

This section presents a pre-feasibility evaluation of Zooma along technical, sensory, peak-period operations, pricing and economic dimensions.

### A. Technical Feasibility

Energy calculations for the Gazelle design have shown potential for a technically feasible solution. Table 1 shows energy use by Gazelle in terms of watt hours (Wh) under four different plat possibilities: 4-seater passenger (full) commute, 6-seater passenger commute (full and empty) and 2-pallet freight plat. Low energy use stems from the low weight of the vehicle (plat), and thus a very high payload-to-weight ratio, as well as from its very aerodynamic shape. The low vehicle weight and low drag of the vehicle body result from simplifying the propulsion, control, energy and levitation mechanisms and vesting significant aspects of these in the fixed track. This approach also yields significant benefits to reliability and near-zero maintenance requirements, both critical to a full automation outcome.

**Table 1 Gazelle Energy Use for Typical Payloads**

Item	Unit	4-Seater Commute Plat	6-Seater Commute Plat	2-Pallet Freight Plat	Empty 6-Seater Commute Plat
<b>Trip and Payload Details</b>					
Trip Length	km	11	11	36	11
Net weight	kg	360	540	740	0
Gross weight	kg	560	780	900	220
Payload ratio	ratio	1.8	2.3	4.6	0
<b>Trip Energy by Component</b>					
Raise lift	Wh	5	7	8	2
Accelerate	Wh	89	121	143	35
Decelerate	Wh	-30	-41	-49	-12
Open air drag	Wh	178	221	676	154
Piston effect drag	Wh	85	153	389	37
Compression	Wh	428	581	2310	168
<b>Trip Total</b>	Wh	<b>754</b>	<b>1041</b>	<b>3476</b>	<b>384</b>
<b>Distance Averaged Energy</b>					
Energy per km	Wh/km	69	95	97	35
Energy per passenger km	Wh/passenger km	17	16	-	6
Energy per tonne km	Wh/tonne km	-	-	130	-

Key elements of the calculations include the following:

- Propulsion is provided by a coreless linear synchronous motor utilising high-performance permanent magnets.
- Levitation is provided by a novel air compressor design. The compressor needs to be proven before feasibility of the Gazelle system can be assured. The energy figures for compression are derived from characteristics of a Computational Fluid Dynamics (CFD) design of a closely related compressor type.

Gazelle design costing references an off-the-shelf linear motor. However, redesign is required to increase its velocity from 10 metres (30 feet) per second to 30 metres (100 feet) per second. Solar panels are standard off-the-shelf units.

The Gazelle design makes use of high performance flywheel energy storage and ultra-capacitors to ensure continuity of energy supply to maintain uninterrupted transport function. These high performance elements are still under development. However, the ultra-capacitors are expected to be on the market by the time Gazelle is piloted. The Fradella high efficiency flywheel is in prototype development at University of California, Berkeley<sup>xxxiv</sup>. The basic ultra-capacitors are off-the-shelf items and used currently in transport (for example, Maxwell BMOD0063 P125 04). The preferred high performance EESor ultra-capacitors are in pre-commercial development<sup>xxxv</sup>.

An enclosed track (or tube) instantly creates an issue with trapped air impeding vehicle movement inside the tube, the so-called 'piston effect'. A vehicle in a tube is turned into a ram, pushing air down the length of the tube. Energy is wasted and vehicle progress is



retarded. Any tube diameter widening to reduce the piston effect has to be counter balanced against tube diameter narrowing possibilities that facilitate construction cost reduction and visual amenity improvement.

The energy calculations present the drag of the vehicle as if the vehicle is travelling in open air. The drag attributable to blockage within an enclosed tube is then added. Two-dimensional solid blockage factor corrections, and wake blockage corrections, are made to arrive at the Piston-effect drag figure. Importantly, the plat shroud is teardrop shaped, without any protuberances or disturbances such as external mirrors, aerals, radiator cooling ports, wheels and wheel arches, windscreen wipers or recesses. Accordingly, the plat shroud is an aerodynamically clean symmetrical streamlined (teardrop) shape that has a very low co-efficient for drag. The very low drag co-efficient is critical to minimising the piston-effect.

Table 2 shows that Gazelle has competitive energy efficiencies with its key rivals in the transport market, particularly in passenger transport. In the passenger segment, Gazelle exhibits energy use in the range of 16 to 29 watt hours (Wh) per passenger kilometre while indicative energy use for rival modes as a group range from 60 to 317 Wh per passenger kilometre. In the freight segment, Gazelle is calculated to use 130 Wh per tonne kilometres compared with a range of 67 to 139 Wh per tonne kilometre for key existing modes. Further research and development is required to verify full technical feasibility: specifically, detailed engineering design, full-scale wind-tunnel testing and prototyping. However, the underlying design approach of Gazelle has shown resiliency in the face of challenge.

**Table 2 Comparative Energy Use for Typical Payloads for Alternative Modes**

<b>Mode</b>	<b>Units</b>	<b>Current</b>	<b>Future</b>
<b>Passenger</b>			
Zooma (direct)	Wh/passenger km	-	16
Zooma (return+stops)	Wh/passenger km	-	29
Urban rail	Wh/passenger km	139	92
Rail - high speed	Wh/passenger km	153	83
City bus	Wh/passenger km	317	-
Light Rail	Wh/passenger km	224	-
Automobile, 2006 (1.57 passengers)	Wh/passenger km	211	-
Plug-in Prius (2 passengers)	Wh/passenger km	74	-
Boeing 787 Dreamliner (90% load, long trip)	Wh/passenger km	97	-
MagneMotion M3 (direct)	Wh/passenger km	-	60
<b>Freight</b>			
Zooma	Wh/tonne km	-	130
Urban rail	Wh/tonne km	139	83
Rail - suburban	Wh/tonne km	97	67

Source: Glazebrook<sup>xxxvi</sup>. Thornton<sup>xxxvii</sup>.

## **B. Sensory Feasibility**

Yantis<sup>xxxviii</sup> suggests sensory analysis as a quality assurance technique for new products like Gazelle. This section provides a qualitatively-based comparison of the physical attributes of Gazelle to those of its key competing mode, the road transport system, along visual, sound, smell, collective and mental attention dimensions.

### ***i. Road Transport***

The road transport mode is a system consisting of roads (a layer of gravel and bitumen or concrete on the surface of the earth) down the middle of every street. In this case, a ‘street’ is a line of houses facing another line of houses, with a public space between the lines that allows for physical access to houses. The mode’s vehicles – cars and trucks – travel (move) on the roads. The vehicles are parked on the side of the roads, inside private garages or in public or commercial car parks when not in use. There are many road signs, traffic lights and traffic and safety devices like roundabouts, guide posts, reflectors and road markings (visible and audible). There are overpasses, underpasses, elevated roadways, freeways, fences and walls, sound walls, tollways, toll booths, bus ways and bus stations. There are considerable cuttings through the landscape and volume-equal embankments. There are bridges and tunnels. There are multi-storey car parks, and large scale ground-level car parks. There are also accident scenes. There are exhaust fumes, particulates and smog. There is road noise, screeching tyres, car engines, horns and sirens. The road transport mode is primarily powered by liquid fossil fuels and the fuel distribution system itself forms part of the road transport system such as petrol stations, fuel depots, oil refineries, oil pipelines, oil tankers, oil production facilities, oil exploration facilities and oil spills. Moves to electric cars would

acquire all the visual elements of the ‘hydroelectric chain’, or the ‘coal-fired electricity generation chain’. People need to keep an eye out or an ear out for cars at all times: our sensory systems are designed to track movement. Mentally attending to moving cars is a useful survival skill as they can kill or maim you or your loved ones.

All of these are visual, aural, olfactory, touch or mental attention elements. Many elements are large and block the visual scene behind them, either permanently or temporarily. A number of elements are intentionally designed to be highly visible and attention-drawing (for example, signage, guide elements and reflectors, traffic lights, tail lights and indicators). Many elements are lit at night. There is street lighting (primarily for personal safety) and road lighting. All moving vehicles have headlights on at night. In fact, there is considerable light pollution arising from the road transport system. This light is readily visible from space at night.

## *ii. Gazelle*

The Gazelle mode is a system consisting of elevated tracks down the middle of every street. The elevated tracks are 2.8 metres (9 feet) in diameter, and have ground clearance of 2.3 metres (7.5 feet). The track is supported by pylons and access points, which incorporate rapid lifts and serve as Micro-Post Offices (MPOs). These features are the primary visual elements of the system. By placing the track in the centre of the street, the angular impact is at its least because the smallest angle to the sky is used, and is equal for homes on either side of the street. The elevation of the track allows people to see the ground storey of the dwellings on the other side of the street, but typically not their rooves or first storey. People can move safely into the street and underneath the track to get a greater uninterrupted vertical angle of vision.

The mode’s vehicles (plats) move inside the tracks. No mental attention is required for the vehicles: most of the movement is above eye-level and hidden by the track, and in any case, there is no possible way for the vehicles to run you down in the street as cars can do. Gazelle runs silently and produces no gaseous emission of any sort. The vehicles are parked within the track or in an access point when not in use. Light Electric Vehicles (LEVs) are an integral part of the system. These LEVs are carried within the track, but then may venture into the street space. These LEVs are smaller and very much lighter than road vehicles and are speed-limited to 40 kilometres per hour. Amenities such as hand trucks and flat-bed trolleys are stowed within the associated street furniture next to the access points. There are bridges and tunnels; however, these structures are of a smaller scale and lighter than for road transport – only needing to support a maximum of 300 kilograms per metre (200 pounds per foot) above track weight. The solar panels on the roof of the Gazelle track may just be visible from the ground, sourcing all the energy required for the system. So there are no other visual elements such as that needed for the fossil fuel chain, the hydroelectric chain, or the coal-fired electricity generation chain.

‘All’, and there appears only a few, of these are visual, aural, olfactory, touch or mental attention elements. The track, pylons and access points are large and block the visual scene behind them, permanently. However, if both side walls of the access points are transparent, then visual blockage would be reduced. The limited number of LEVs are small, and block the visual scene behind them temporarily. The only elements intentionally designed to be highly visible and attention-drawing are the post-office box doors. These are small and visible temporarily at the time the transport user is locating their box. Some elements are lit at night

in a subdued way. There are no headlights on Gazelle vehicles, only LED cabin lighting. There will be minimal light pollution arising from Gazelle. Gazelle's track system would not be visible from space. Street lighting can be redesigned to be lit from underneath the Gazelle track with highly efficient LED lighting that emits even lighting.

### *iii. Conclusion*

Road transport infrastructure imposes on people's senses in a number of ways. Zooma infrastructure imposes on people's senses primarily through the visual impact of the elevated track. However, a critical difference between the road transport system and Zooma needs to be taken into account: the energy manufacturing and distribution system — Gazelle is far more compact. The sound and smell attributes of the Gazelle system will be an improvement compared with the road transport system given Gazelle's use of non-contact air-cushion levitation and non-contact electro-magnetic propulsion rather than internal combustion engines and 'rubber-on-road' traction. The total sensory experience and the 'internal sense' — mental attention — of Gazelle compared with the road transport system is a complex issue, however, Gazelle's total grade separation between pedestrians and vehicles should certainly ease the mental burden. When the automobile emerged to replace animal-drafted vehicles in the late nineteenth century: hard-nosed transport benefits, not sensory impacts, were the primary driver of the automobile's success. Non-functional sensory impacts are transitional issues.

### **C. Peak-Period Operational Feasibility**

Zooma was designed to conquer the mounting road traffic congestion issue evident in all large and growing urban areas, from medium-sized global cities to the world's largest urban agglomerations<sup>xxxix</sup>. In the example below, Sydney, Australia (a medium-sized global city) is used to assess what capacity volume is added via a Zooma network to give guidance on the feasibility of congestion reduction. The Zooma network size for Sydney is estimated to be 21,000 kilometres (13,000 miles) of track, based on the length of the street and road network.

For Sydney, calculations show that Zooma's volume capacity is 4.6 million passenger trips per hour in peak periods, assuming predominant traffic flow in one general direction. This calculation uses 252,000 plats, and assumes a 50/50 split between 4-passenger plats and 6-passenger plats, or an average 5 persons per plat. Capacity growth on the same track network can be attained by using a greater number of plats, up to some characteristic limit. For example, by doubling the number of plats to 500,000 (at an additional cost of A\$2.5 billion) Zooma's volume capacity rises to 9.1 million passenger trips per hour in peak periods. The nature of trips that are generally made would mean that 4-passenger plats would be employed closer to the city in the inner and middle rings, whilst the 6-passenger plats would be more suitable for longer distance commutes with trip origins and destinations for locations within the outer ring.

The Zooma deployment example for Sydney has been designed to cope with the passenger and freight capacities expected in the year 2050. That is, no further investment is required to cope with increasing trip volumes between 2020 and 2050. Further, assuming a population for Sydney in 2020 of about 5.3 million<sup>xl</sup>, a Zooma volume of 4.6 million passengers per hour in peak periods deals with all worker and education commuters in a timely manner. This assertion considers provisions for picking up and dropping off all passengers to obtain fully occupied plats, as well as the return of the empty plat for the next cycle of commuters. The

average speed of plats is 80 kilometres per hour, including all pick-ups and drop-offs. This average plat speed yields a 33 per cent trip time improvement over the non-congested (or off-peak) average speed of 52 kilometres per hour on Sydney's roads<sup>xli</sup>. This plat speed also represents a very significant improvement over Sydney's congested AM average speed of 34 kilometres per hour, or the congested PM average speed of 40 kilometres per hour for the road mode as cited in Glazebrook<sup>xlii</sup>. Energy efficient trips up to 130 kilometres per hour are possible so commuter trips from the suburb of Campbelltown in Sydney's outer ring to the CBD could take as little as 20 minutes.

Drop-off/pick-up queuing, and potential congestion, is resolved by using the optimised routing capabilities of the network to route through-traffic around any stopping-traffic. On high-volume routes, advantage is taken of the parallel distributed streets to rotate a local-access-only route between the streets, with the other streets being through-traffic. The ratio of local-access-only routes and through-traffic routes can be dynamically determined depending on traffic volume. High-volume streets displaying inward and outward peak behaviour can be fitted with bi-directional Gazelle tracks. In this way, additional inward or outward routes can be deployed depending on the principal traffic flow.

Drop-offs and pick-ups are quick and easy. Passengers have direct and quick access to seating or to the exit. The plat does not block the track during stops. Other plat traffic continues overhead unimpeded. Routing and passenger selection aim to pick up one couple per plat to help reduce the number of pick-ups and drop-offs. Commuter drop-offs may 'pool' passenger disembarkation points (in line with the passenger's specific service conditions) to help keep drop-offs to a minimum, and help to reduce congestion during peak hours in the Central Business District (CBD).

High-volume access points would be utilised for high throughput locations such as entertainment or sports venues, or in the CBD. With many distributed Zooma access points, congested congregation as tends to occur at train stations or bus stops in CBDs is very substantially reduced. Passengers are also delivered much closer to their place of work compared with bus interchanges and train stations.

Further, an underground Zooma network in CBD precincts is achievable due to the relatively small diameter of the Gazelle track combined with the elimination of the need to remove motor vehicle exhaust fumes. Such an underground network would serve high-volume access points located within CBD building's basement car parks. Suitable depth can be determined to avoid subterranean utilities. With many high-volume access points available in the CBD (and under the CBD), there is plenty of scope to avoid congested drop-off points. And if capacity is in short supply, then the Transport Futures Market utilises pricing to spread the otherwise congested traffic according to an economically efficient regime.

In summary, Zooma is able to utilise a combination of mechanisms, including speed, globally optimised routing and passenger selection, to provide a high peak-volume carrier with plenty of capacity. And instead of 'hitting a wall' during peak periods as road transport does, Zooma is able to use market-based mechanisms to spread traffic load in a globally co-ordinated way so that congestion is avoided. Zooma's operational feasibility in peak periods is assured.

#### **D. Pricing Feasibility**

Transport pricing can be a complex issue because of the multiplicity of sustainability objectives, the institutional separation of infrastructure from operations, pricing from tax components of charges and transport modes from each other<sup>xliii</sup>. In road transport, the shift to user charges such as tolls has allowed greater cost recovery for roads. Satellite positioning and wireless data transfer technologies have also allowed these tolls to closely reflect the time and place of use of vehicles. Variable tolling is increasingly being utilised to manage traffic demand<sup>xliv</sup>, essentially inducing people to travel less or to seek alternative transport means during peak periods. Tolls and other taxation instruments reflecting environmental performance are also progressively being utilised to accelerate deployment of cleaner fleets. However, Zooma removes or internalises these social and environmental costs inherent in existing transport modes. Further, Zooma has full system capability for efficient pricing schedules.

Gazelle's energy efficiency combined with Zooma's automation translates into mode pricing that is very competitive against existing transport modes. Full operational cost recovery, plus full asset cost recovery where principal is paid off within 30 years is assumed in the Zooma pricing. Zooma has a significant infrastructure cost structure and very few variable costs. Other costs such as consumables, cleaning and labour at the service centres do not vary greatly with system use. Accordingly, the more passenger or freight kilometres utilised, the greater the fixed costs are amortised. Gazelle's variable costs are very low due to its low energy requirement, near-zero maintenance operation, automation and renewable solar energy source based on fixed assets. Human supervision would increase with more trips, although such supervision would be leveraged by computer-vision supervision.

In this paper, pricing estimates are established using a case study city of Sydney, Australia. To allow fair comparison of the cost of different transport modes to transport users in Sydney, Glazebrook<sup>xlv</sup> categorises transport costs into three groups: externality and subsidy, other private costs and variable user costs. Table 3 defines what costs are included in each of three groupings. For cars, the biggest private cost is fuel at A\$0.12 per passenger-kilometre (based on A\$1.40 per litre in 2006, a similar level in 2013) while the largest external cost is congestion at A\$0.20 per passenger-kilometre. For buses and rail, public funding, congestion and greenhouse emissions are the biggest contributors to their Externality and Subsidy component. For Gazelle, there are no externalities, although two pricing scenarios are considered: without a subsidy and with a subsidy equal to 100 per cent of Zooma's annual interest cost. Fares are the only variable user cost in the case of trains, buses and Gazelle, and no other private costs are incurred by users of these three modes.

**Table 3 Costs Inclusion by Mode**

Item	Cars	Trains/Buses	Gazelle No Subsidy	Gazelle With Interest Subsidy
<i>Externality &amp; Subsidy Costs</i>				
	Pollution	Pollution	-	Government
	Noise	Noise		subsidy to
	Congestion	Contribution to congestion		operator for
	Accident costs above insurance	Accident costs		interest
	'Free' or subsidised parking	Government		payments over
				30 years

General revenue payments to motor registry (RTA/RMS)	subsidies to operators		
Local government rates used on roads			
<b>Other Private Costs</b>			
Registration	-	-	-
Insurance			
Depreciation			
Maintenance			
<b>Variable User Costs</b>			
Petrol	Fares by users	Fares by users	Fares by users
Tolls			
Paid parking			

Table 4 compares cost estimates for three different existing transport modes for Sydney, as compiled by Glazebrook<sup>xlvi</sup>, and compares these to Gazelle's two pricing scenarios. Since Glazebrook's costings are expressed on a per passenger kilometre basis, Gazelle pricing shown in the table is based on a Zooma passenger revenue share at 60 per cent; commercial and freight account for the remaining revenue.

**Table 4 Costs by Selected Mode in Sydney (A\$ per passenger-kilometre)**

2005-06 data for cars, trains & buses. Pricing estimates for Gazelle.

Item	Gazelle		Cars	Trains	Buses
	<i>No Subsidy</i>	<i>With Interest Subsidy</i>			
Externality and Subsidy	-	0.08	0.38	0.37	0.38
Other Private Costs	-	-	0.34	-	-
Variable User Cost	0.20	0.09	0.14	0.11	0.19
<b>Total</b>	<b>0.20</b>	<b>0.17</b>	<b>0.86</b>	<b>0.48</b>	<b>0.57</b>

Table 4 shows that Gazelle's fare price would be 20 cents per passenger kilometre without subsidy and on a fully funded basis. By comparison, Sydney transport users pay 14 cents for cars (48 cents when other private costs are included), 11 cents for trains and 19 cents for buses. On the basis of price alone, Zooma would possibly achieve limited modal shift despite the removal of the many externalities accruing to other modes. The application of full carbon pricing on fossil fuels would be appropriate with Gazelle offering a viable transport alternative for both social and economic reasons. However, the impact on fuel cost per kilometre would be small, and would likely to be significantly ameliorated in the future through improvements in the fuel efficiency of newer cars. However, Zooma does have substantial non-price benefits such as convenience and reduced trip times — not to mention ethical use, with zero-carbon operation.

The cost structure of Zooma may be split into its operating and financing components. Gazelle's true operational cost structure would be charged to transport users if Zooma's

interest payments are subsidised (for 30 years in the Sydney example). As shown in Table 4, Gazelle's fare price would be only 9 cents per passenger kilometre with an 8 cents interest subsidy on a per passenger-kilometre basis. At a fare level of 9 cents, modal shift to Gazelle would be considerable given the speed, safety and coverage of the Zooma network. Further, any interest subsidy borne by governments with increased use of the Gazelle mode would be reduced to the degree that subsidisation of other modes lessens, lower road costs and bus service provision expenses accrue and tax revenues grow from higher productivity and economic activity.

Clearly, Gazelle is feasible on a pricing basis given the assumptions outlined in this paper. However, can governments justify providing an interest subsidy (for 30 years in this example) to Zooma so Gazelle can be supplied at pricing rates that reflect its underlying cost structure? This value proposition is assessed in the next section on economic feasibility.

### **E. Economic Feasibility**

Australia's infrastructure priorities are assessed using the Benefit-Cost Analysis framework. Benefit-Cost Analysis allows the systematic comparison of different types and different time profiles of costs and benefits. The focus of the Benefit-Cost Analysis is on the difference between benefits and costs of a scenario compared with the baseline. A Benefit-Cost Analysis is difficult to produce for a new transport mode without a prototype, particularly using the best practice principles as outlined in the Infrastructure Australia document<sup>xlvii</sup>. However, two factors reduce the scope of the benefits and costs that need to be assessed: first, Zooma's operating costs are very small relative to Gazelle's infrastructure costs, and second, Zooma's cost structure for pricing is assessed to be very low compared to other modes under the interest subsidy scenario. If these costing calculations are reflective of Zooma's eventual cost structure, then the Benefit-Cost Analysis exercise becomes more about how much market share Zooma would be able to achieve, and how quickly any market gains would occur. Another key uncertainty is how governments and societies would respond to the many possible socio-economic transition impacts of a Zooma deployment.

Key methodology assumptions are as follows. First, a discount rate of 7 per cent (real) per year is used to discount future benefits to the current day. Second, all costs and benefits reflect 2013 dollar values. Finally, the Zooma scenario commences in 2020 for illustration purposes. Consequently, the discounting time horizon chosen is the thirty-year period between 2020 and 2050.

#### ***i. The Base Case***

The case study city chosen to apply Zooma to is Sydney, Australia. Sydney's current population is around 4.6 million people with a road network estimated at around 21,000 kilometres (13,000 miles) in length. The Base Case scenario assumes the extension of existing trends for population, passenger trips and pallet freight and has been derived from Bureau of Transport Statistics forecasts<sup>xlviii xlix 1</sup>.

#### ***ii. The Zooma Scenario***

A five-year Sydney infrastructure roll-out plan occurs: completing the South-West by 2021, the South and East by 2022, Central to West regions by 2023, the North West by 2024 and the North and North East by 2025; an average daily roll-out plan of 11.5 kilometres



(7,000 miles) of track. Annual average infrastructure spend over the 30 years is estimated at around A\$4.2 billion given system set up costs at just under A\$7.5 million per kilometre (A\$12 million per mile). However, total expenditure is ‘front-loaded’ into the first 5 years.

Zooma’s mode share is set at 80 per cent in the passenger travel market and 70 per cent of the truck pallet freight market (pallet freight accounts for 70% of the total truck freight). Migration from existing modes to Zooma is surmised to be rapid given Zooma’s time savings, cost relativities, ubiquity and automation advantages. Importantly, city-based trips are replaced in the modelling while motor vehicles are made redundant only on a turnover basis.

Under Zooma, urban consolidation would intensify and city footprint expansion would be limited; similar to the ‘Inner Ring-Middle Ring’ alternative growth scenario for Sydney as outlined in Centre of International Economics report<sup>li</sup>. Hence, the network size is assumed to remain at 21,000 kilometres into the future. Sydney’s population density expands from around 400 persons per square kilometre to around 600 persons per square kilometre in this scenario, a population density that remains much lower than in most global city agglomerations<sup>lii</sup>.

### *iii. Benefits*

Table 5 summarises the key elements of the methodology used to estimate the economic benefits arising from a Zooma deployment in Sydney. The benefits definition used is narrow. The scope of the transport market is limited to passenger and pallet freight only. The majority of benefits are generally derived from the first-round economic impacts of Zooma replacing the bulk of city-based road transport trips, thus nullifying the bulk of road transport’s subsequent direct costs and external costs. Any justification for the benefits attributed to Gazelle comes down to an argument for overwhelming modal shift within the city from road transport to Zooma.

The second-round impacts and wider economic benefits from a Zooma deployment would be significant but are, by and large, not accounted for. First, any induced demand impacts because of reduced trip times, lowered trip costs and increased accessibility created by Gazelle are ignored. Second, the deep integration of automated and digital transport across an economy would lead to very substantial cost savings, and are unaccounted for. Third, any space saving that might arise from redundancy of land dedicated to road use, on-street and off-street car parking and fossil fuel distribution to be employed in alternate land uses is not modelled. Finally, agglomeration economies arising from better land use planning possibilities as outlined by SGS Economics & Planning<sup>liii</sup> are not measured.

**Table 5 Methodology for Measuring Benefits for a Zooma Deployment — Sydney, Australia**

Scope of Benefit	Modelling Approach and Sources
Fuel Savings	

*Scope of fuel savings is limited to petrol and diesel; Liquefied Petroleum Gas use is not modelled. Petrol fuel use excludes Sydney weekend and holiday car travel.*

Fuel use per capita is held constant. Base Case fossil fuel use is escalated with population only. Petrol and diesel prices are assumed to rise over the 30 year period. For example, petrol price rises from A\$1.69 per litre in 2020 to A\$2.90 per litre in 2050. A similar rise is assumed for diesel. Fuel use & fuel price projections source: Bureau of Infrastructure, Transport and Regional Economics<sup>liv</sup>.

### **Other Transport Mode & Industry Savings**

*Paid parking*

Estimates for paid parking in the Sydney CBD by 2020 is A\$1 billion, Sydney Airport A\$0.4 billion, plus parking fees in the remainder of Sydney; totalling A\$2 billion. These values expand with population. Paid parking value source: Lentini<sup>lv</sup>.

*Deferred car industry subsidy payments & tariffs*

Car industry subsidy payments and tariffs value of A\$1.6 billion in 2011 for Australia is claimed. Measure is calibrated to grow in line with the Sydney population size in the projection years. Zooma deployment in Sydney is likely to result in a transitioning of manufacturing from cars to robotics and automation, plus bulk production of track & plats. Car subsidy value source: Productivity Commission as reported in Bosworth<sup>lvi</sup>.

*Deferred road network investments & maintenance*

Sydney Metropolitan Transport Plan indicates A\$21.9 billion over 10 years. Initial estimate value of about A\$2.2 billion expands with projected population. Source: Engineers Australia<sup>lvii</sup>.

*Deferred taxi fares*

Taxi trip value of A\$1.5 billion is assumed to be displaced by Gazelle. Deferred taxi fare value expands with population. Benefit source: Select Committee on the NSW Taxi Industry<sup>lviii</sup>.

*Deferred bus fares*

Bus trip value of A\$1 billion is assumed to be displaced by Gazelle. Deferred bus fare value expands with population. Benefit source: IBISWorld<sup>lix</sup>.

*Extreme weather-related - e.g. inundated road & public transport delays*

Daily congestion figure is upscaled three times for each bad weather day. Initial estimate value of A\$0.2 billion in expands with projected population. Source: Sydney Morning Herald<sup>lx</sup>.

*Displaced road tolls*

Transurban tolls, Harbour bridge and tunnel tolls and eTags projected to 2020. Initial estimate value of about A\$1 billion expands with projected population. Source: Transurban<sup>lxi</sup> and Roads and Traffic Authority<sup>lxii</sup>.

### **Congestion Savings**

2010 industry estimate scaled to 2020. Widely-reported initial estimate value of about A\$7.8 billion expands with projected population. Congestion source: ACIL Tasman<sup>lxiii</sup>.

### **Reduced Non-Congested Trip Time Savings**

Using 'Congestion Savings' as estimate for cost of time - proportional time-saving below the 'no congestion' trip time. Median trip timed on 4-seater plat, 100% occupancy, 1 couple and 2 singles. Initial estimate value of A\$7.4 billion expands with projected population. Congestion source: ACIL Tasman<sup>lxiv</sup>.

### **Productivity Gains**

Sydney Orbital Ring Road productivity estimated at A\$1.8 billion. Productivity estimate for a Sydney fine-mesh network is extrapolated to be A\$5 billion. Initial estimate value expands with population. Orbital Ring Road productivity estimate source: Ernst & Young<sup>lxv</sup>.

### **Health-Related Savings**

*Air pollution*

Upper-end health impact estimate of vehicle emissions in Sydney by Amoako, Ockwell, & Lodh<sup>lxvi</sup> of A\$4.7 billion is initially used, and then grows with projected population.

*Accident-related*

Initial cost of road crashes estimate of A\$2.2 billion expands with population. Accident Cost Source: NRMA<sup>lxvii</sup>.

### No-Buy-Car Savings

Average cost of a new car assumed at A\$20,000, held constant in real terms. Fleet turnover rate is assumed to be 7 per cent per year. Zooma's market share is 80 per cent so 8 out of 10 cars of the 7 per cent are replaced. Motor vehicle numbers source: Bureau of Transport Statistics<sup>lxviii</sup>.

### Carbon Offset

Benefit is modelled as petrol and diesel fuel use savings in volume terms expressed in terms of carbon emission equivalents times the carbon price. Carbon price is assumed at A\$33 per tonne-e in 2020 rising to A\$90 per tonne-e by 2050. Emission equivalents source: Bureau of Resources and Energy Economics<sup>lxix</sup>.

### Other Benefits

*More physically active environment  
- e.g. reduce obesity & diabetes*

Initial cost estimate of A\$0.2 billion expands with population. Benefit estimate source: Matan, Trubka, Newman & Vardoulakis<sup>lxx</sup>.

*Noise pollution - including impact  
on sleep disturbance*

Initial cost estimate of A\$0.5 billion expands with population. Benefit estimate source: Matan, Trubka, Newman & Vardoulakis<sup>lxxi</sup>.

*Sale of excess electricity*

Initial sale estimate of A\$0.25 billion, held constant. Assumes excess Gazelle electricity sold to National Electricity Market at wholesale prices at a NEM average price of A\$25/MWh. Price source: Office of the Tasmanian Economic Regulator<sup>lxxii</sup>.

*Waste collection*

Initial cost estimate of A\$0.3 billion expands with population. Benefit estimate source: Morris & Cameron<sup>lxxiii</sup>.

*Post parcel*

Initial cost estimate of A\$0.5 billion expands with population. Benefit estimate source: Chappell<sup>lxxiv</sup>.

## iv. Costs

Table 6 presents initial costings to supply Sydney with Gazelle and SPS infrastructure. These costings are based on recommended retail prices for the major items. Clearly, a wide range of assumptions lie behind the costings in the Benefit-Cost Analysis. For example, for solar panels, the non-mirror all-solar configuration is used. For supervision of the network in operating costs, supervision costings are based on 21,000 shift-based employees who supply round-the-clock supervision semi-proportionally to demand. Table 6 shows that the total infrastructure spend is estimated at around A\$152 billion given system set up costs at just under A\$7.5 million per kilometre. In comparison, the road construction cost of the Melbourne East West Link project for 6 lanes was around A\$10.7 million per lane-kilometre<sup>lxxv</sup>.

**Table 6 Gazelle Infrastructure Costs for a 21,000 kilometres city network — Sydney**

Item	A\$ billion
Solar panels	15
Flywheels	12
Ultra-capacitors	16
Linear Motor	21
Electricity distribution (cables)	7
Track Structure	19
Track Enclosure	17
Switches/Merges	2
Electrical power switching & control	9
Air Compressors	2

Access Points	20
Plats (vehicles)	3
Service Centres	1
Air Quality Points	4
Computer centres	4
<b>Total Network Cost (A\$billion)</b>	<b>152</b>
<b><i>Average Cost per kilometre (A\$million)</i></b>	<b><i>7.5</i></b>

#### *v. Net Benefits Assessment*

The Zooma paradigm applied to Sydney from 2020 onwards leads to net benefits of around A\$511 billion or may realise economic benefits that could be 5 times the infrastructure costs that are front-loaded into the first 5 years. Table 7 presents a summary of the benefits and costs that are included in the Benefit-Cost Analysis. These results are based on fare pricing that fully covers operating costs (not interest expenses) and allows for full infrastructure cost recovery within 30 years. Additional calculations show that any interest payment subsidy by governments would be covered 12 times by the measure of economic benefits in undiscounted terms.

While the benefit and cost measures in this paper attempt to as much as is possible err on the side of conservatism, a proper risk analysis of the Zooma concept as suggested for mega-projects by Flyvbjerg, Bruzelius and Rothengatter<sup>lxxvi</sup> would need to be made.

**Table 7 Cost-Benefit Analysis for Sydney, Australia**

<i>Discounted Benefit-Cost Ratio</i>	<b>4.9</b>	<i>Discount Rate</i>							<b>7%</b>
<i>Net Present Value (A\$bil, 2013)</i>	<b>489.2</b>								
	<i>2020-2050</i>	<i>2020</i>	<i>2021</i>	<i>2022</i>	<i>2023</i>	<i>2024</i>	<i>2025</i>	<i>2026-2050</i>	
	<i>Cumulative</i>								
<b><u>Costs (\$bil, 2013 \$ terms)</u></b>	<b>e</b>							<i>Average</i>	
Infrastructure Costs	<b>152</b>	32	31	30	30	29	-	-	
Operating Costs (fares full cost recovery)		-	0.2	0.4	0.7	0.9	1.1	<b>1.1</b>	
<b><u>Benefits (\$bil, \$ 2013 terms)</u></b>									
Fuel Savings	435	-	2	3	5	7	8	9	
Other Transport Mode & Industry Savings	337	-	2	4	6	8	11	11	
Congestion Savings	265	-	2	3	5	7	8	8	
Reduced Non-Congested Trip Time Savings	250	-	1	3	5	6	8	8	
Productivity Gains	170	-	1	2	3	4	5	5	
Health-Related Savings	160	-	1	2	3	4	5	5	
No-Buy-Car Savings	157	-	1	2	3	4	5	5	
Carbon Offset	37	-	0	0	0	1	1	1	
Other Benefits	58	-	0	1	1	1	2	2	
<b>Total</b>	<b>1,869</b>	<b>-</b>	<b>10</b>	<b>20</b>	<b>31</b>	<b>42</b>	<b>53</b>	<b>55</b>	

One key uncertainty is Zooma's mode share and one could argue that existing modes could employ new technologies that could result in a far lower Zooma mode share than assumed in the Benefit-Cost Analysis. The benefit measure in Table 7 could simply be reduced by 50 per cent to reflect a halving of the assumed Zooma mode share to 40 per cent in the passenger travel market and 35 per cent in the truck freight market. In this scenario, there would be cost savings compared with the base Zooma scenario. But these potential cost savings are ignored and costs are unadjusted in this low mode share Zooma scenario. The present value of net benefits in the low mode share Zooma scenario are measured at around A\$190 billion or 2 ½ times the full cost of operations and deployment. Gazelle fares on a per passenger kilometre basis could be increased to 15 cents to ensure full infrastructure cost recovery within 30 years. This Zooma's fare of 15 cents per passenger kilometre remains well within the range of feasibility given the 11 to 19 cents pricing range for trains, buses and cars. Any interest payment subsidy by governments would also be covered 5 ¾ times by the measure of economic benefits in undiscounted terms.

Best-practice infrastructure cost estimation also suggests applying a P90 value (that an estimate of project cost should be based on a 90 percent probability that the cost will not be exceeded) should be employed<sup>lxxvii</sup>. On the other hand, best-practice measurement of economic benefits for use in Table 7 would also include full scoping of transport markets, behavioural interaction modelling between modes, induced demand impact modelling and the full assessment of the wider economic benefits. The wider economic benefits would be substantial, stemming from the integration of an automated and digital transport mode into the economy, any land saving that would occur across the road transport and carbon fuel chain (Glazebrook<sup>lxxviii</sup> measures the economic value of real estate devoted to car parking in Sydney in 2005 to be in the order of A\$76 billion alone), and the possibility of significant

agglomeration economies arising from improved land use and transport planning strategies based around Zooma.

### **VIII. Summary and Conclusions**

The Zooma infrastructure paradigm applies a fully automated passenger and freight system called Gazelle that is leveraged by a consumer and business-accessible built-in logistics system called the Super Postal Service. Gazelle uses light small vehicles moving inside an elevated track way along every street. In this way, Zooma provides independent mobility and presents people with a carbon-free alternative to the car without having to forego the convenience of modern life. Gazelle could replace all cars, taxis, buses, light truck and palletised goods haulage within a city. However, Gazelle could not replace (non-palletised) heavy road transport. Gazelle articulates very well with other modes of transport, particularly rail.

Zooma transport infrastructure represents a feasible pathway for global cities seeking a paradigm shift in their transport and land use planning strategy. Gazelle offers the opportunity to conquer the mounting road traffic congestion issue evident in medium sized global cities through to the world's largest urban agglomerations. Reduced conflict involved with urban consolidation and renewal can occur because transport costs can be reduced, trip times are easily shortened, and land dedicated for transport and carbon-fuel manufacturing and distribution is diminished. Since Gazelle effectively makes transport digital, the Super Postal Service is able to host with other business-to-business systems and develop transport futures markets. Deep integration of a digitally-based automated transport mode into the household, business and government sectors would deliver significant economic transformation in many global-city economies.

On the evidence presented for Sydney Australia, Zooma is able to utilise a combination of mechanisms, including speed and globally-optimised routing, to provide a high-peak volume carrier with plenty of capacity, and lead to peak hour trip-time reductions by two-thirds. Unlike road transport peak periods at peak periods, Zooma exhibits graceful degradation under volume pressure by the use of market-based mechanisms to spread traffic load over time in a globally co-ordinated way and economically efficient manner. Gazelle is assessed to be very price competitive against incumbent modes. Gazelle's fare – based on its underlying cost structure – would be 9 cents per passenger-kilometre compared with 14 cents for cars, 11 cents for trains and 19 cents for buses. Besides being cheaper, Gazelle's contact-less propulsion, levitation and switching ensures reliable, long-lasting and efficient operation. The Zooma paradigm applied to Sydney from 2020 onwards leads to net benefits of around A\$500 billion or economic benefits that are 5 times the cost of the infrastructure. A preliminary risk analysis shows that there are still substantial net benefits to Sydney even if Zooma's mode share is reduced to half that assumed in the base Zooma scenario. Further, the benefit measure applied is conservative, and does not include the wider economic benefits of transport automation, digital integration and enhanced metropolitan planning possibilities.

The Zooma concept warrants further development so the concept can be examined on its merits in any global city's metropolitan urban transport and land use planning strategy. More research is required to advance the proposed concept through to proof of concept of the levitation mechanism, and to design and engineering of propulsion and switching mechanisms, in order to build a prototype and refine costing estimates. Once a Gazelle

prototype has been demonstrated, a multidisciplinary, international project-based approach would best address the further challenges in deploying such a revolutionary system into society.

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# **The Potential of MISTER Personal Rapid Transit to Sustain the Mobility and Development of Modern Communities**

Richard F. Di Bona<sup>a\*</sup>  
Olgierd S. Mikosza<sup>b</sup>

**Abstract:** The Potential of MISTER Personal Rapid Transit to Sustain the Mobility and Development of Modern Communities, including: 1. Introduction: the role of transport in Schumpeterian innovation waves; 2. Key challenges faced for public transport investments: – CapEx, OpEx and the subsidy requirements of most public transit systems; – Providing a level of service sufficient to persuade motorists from their cars and making transit itself an attractive choice; – Mass personalisation in consumer markets; – The issue of pedestrian, vehicular and junction conflicts; – Engineering problems with retro-fitting good solutions into existing urban environments; 3. Outlining Personal Rapid Transit (PRT), comparing some of the systems in the market place to show how Second Generation PRT could likely address the above issues and ISNGI's stated Grand Research Challenge, including: – Summary results from transport modeling-based analysis; – Explanation of some features specific to MISTER PRT.

**Key words:** Transport; Personal Rapid Transit; Innovation; Sustainability; Mobility; Commercially Viable Public Transport; MISTER PRT

## **I. Introduction**

This Paper discusses transport innovation in a Schumpeterian context, required of any true next generation infrastructure; such public transport infrastructure must be attractive to potential users, to sustain modern communities' mobility, and development. The MISTER Personal Rapid Transit system is introduced and preliminary results from *EMME* modelling of a potential application in the city of Opole, Poland are presented. This shows MISTER has the potential to overcome many of the challenges faced by traditional transport infrastructure solutions, not only being more attractive to potential users, but also being substantially less costly than traditional public transport; likely obviating the need for public subsidies and being much quicker to implement.

## **II. Transport in Innovation Waves**

Consolidating others' preceding works, Schumpeter<sup>1</sup> identified a series of business cycles. This included the 48-60 year Kondratieff Wave<sup>2</sup>. The Kondratieff Wave is based on the development of new technologies, business sectors, and postulates periodic "creative

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<sup>a</sup> Independent Transport Planning Consultant, Hong Kong

<sup>b</sup> President, MISTER Corporation, Auckland 1052, New Zealand

\*Corresponding author: Richard Di Bona [rfdibona@yahoo.com](mailto:rfdibona@yahoo.com)  
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destruction” as being intrinsic to industrial capitalism<sup>3</sup>. Faber<sup>4</sup> summarised key characteristics of this cycle, including:

- Before and during the beginning of Upswings there are profound changes in industrial techniques (based on new technologies).
- Agricultural prices decrease during downswings; industrial prices hold steady or fall slightly. During upswings, commodity price increases can create broader price inflation. Interest rates also follow this cycle.
- Upswings are characterised by brevity of depressions and intensity of booms; the opposite being true during downswings.

Maddison<sup>5</sup> estimated real global GDP per capita rose 2.90% p.a. from the 1950s-1970s (Kondratieff Wave upswing); but declined to 1.11% p.a. until the 1990's (downswing phase). Faber<sup>4</sup> noted the role that breakthroughs in transport technology have played in driving Kondratieff Wave upswings, namely: canals and roads (1787 onwards); railways, particularly the railroadisation of America (1842 onwards); and, aerospace (since WWII). The advent of the motor car could also be added to this list. Faber posits that the fifth Kondratieff Wave commenced around 2004, being driven by breakthroughs in telecommunications and information technology. Such breakthroughs do not occur at distinct points in time; rather, as multiple technological advancements disseminate, advancements in a number of areas eventually reach critical mass, enabling stepwise rather than merely incremental improvements. These then disseminate, ultimately reaching their own critical mass. In the case of computing, advancements have been historically described by “Moore's Law”, that computing power doubles and prices halve roughly every 18 months<sup>6</sup>. This enables concepts to become cost-effective realities, in accordance with Schumpeter's observations<sup>1</sup>, driving down costs for other activities, realising wider economic gains. In part enabled by such recent breakthroughs, it could be argued that society has entered an era of mass personalisation, with aspirations and expectations now demanding increased personalisation of product and service offerings, including for urban transport.

### **III. The Challenges for Next Generation Infrastructure**

The key challenge for any next generation infrastructure is to continue the process outlined above: driving down costs both to society as a whole and to the individual user, relating to both construction and operation. The benefits of such infrastructure over-and-above such cost savings should increase. For transport infrastructure, this means increasing mobility and personalisation options for the individual; underpinning sustainable development and economic growth of communities. This should be achieved within existing economic conditions, namely an era of austerity following the recent and ongoing global financial crisis. Thus cost savings are a key challenge.

### **IV. Key Challenges for Public Transport**

Recent history has seen tremendous growth in car ownership. Globally from 1960 to 2002 incomes rose 2.0% p.a. in real terms, whilst the motorisation rate grew 4.6% p.a. over the same period<sup>7</sup>. This could be taken both as a cause and evidence of increasing aspirations for personalised transport and mobility; especially when this growth in car ownership is considered in the context of substantial investments over the same period in various, often capital-hungry public transport infrastructure projects. For example, Scholtz-Knoblach

surveyed typical system capital costs per km to be US\$52-260m for heavy metro; and, US\$13-91m for light rail<sup>8</sup>.

Four-stage transport models, as described in Ortúzar and Willumsen<sup>9</sup> take into account a wide variety of transport journey characteristics when being calibrated and used in forecasting. These can include: in-vehicle time (by mode), fares, waiting time, walk time (or distance); and, number of interchanges (given that uncertainty regarding journey times generally increases with the number of interchanges required). Yet, the performance of transport models is often poor when outturn patronage is compared against ex ante forecasts thereof, as shown in Flyvberg, et al. for mass transit projects<sup>10</sup>. Di Bona<sup>11</sup> notes that this may be in part due to the transformational nature of introducing or significantly extending the reach of mass transit networks; but that uncertainty in rapidly evolving environments is also a contributory factor, something which current global economic uncertainty will likely cause even in traditionally stable and mature urban centres.

However, more fundamentally strategic transport models typically require substantial simplification of land use patterns (zones) and transport networks. By concentrating on the strategic overview, weak links in public transport networks, such as pedestrian severance caused by a major road, poorly maintained sidewalks, or poorly designed interchanges can result in barriers to public transport usage not considered in models<sup>11,12</sup>. Moreover, issues pertaining to institutional coordination can result in disjointed planning and nonintegrated transport networks not considered in model forecasts<sup>12,13</sup>. Added to which, due in part to issues of computing power and data availability, pedestrian level-of-service has often been under-emphasised<sup>13</sup>.

Given that such shortcomings affect the viability of transport infrastructure investments, they reduce the probability of further projects being approved<sup>11</sup>. Next generation transport infrastructure projects, in line with Schumpeter's requirements<sup>1</sup> need to be viable despite these widespread challenges; ideally finding a way to overcome the problem of pedestrian accessibility in particular<sup>14</sup>.

## **V. Personal Rapid Transit**

The Advanced Transit Association defines Personal Rapid Transit (PRT) as an automated guideway transit system in which all stations are on bypasses, the vehicles are designed for a single individual or small group (family or friends) travelling together on a segregated network, and trips are nonstop without transfers. In other words:

- PRT offers point-to-point journeys, neither requiring interchange between "lines" nor stopping at intermediate stops, so journey times are quicker even than metro.
- Stations can be much closer than metro or LRT and much smaller, so passengers do not have to walk as far to/from the system.
- Passengers travel on their own or with a small group of friends, colleagues, and/ or family, i.e. not with strangers.
- Unlike surface level light rail or bus rapid transit, it will not interfere with the operation of traffic junctions or other road users or pedestrians.

As such, PRT could be said to offer significantly faster, safer, more comfortable journeys than traditional public transport modes. Yet due to efficiency and cost advantages, PRT can

be offered to customers at fare levels similar to those charged by traditional public transport modes, without the need for subsidies. Given that stations can be 100m-300m apart (depending upon the specific PRT system) and that all PRT systems are smaller and more lightweight than monorail (not to mention metro), PRT offers improved accessibility and deeper direct market penetration than traditional rail-based transport modes: either in its own right or as a feeder to metro. Moreover, PRT could be described as having the environmental benefits of public transport (including the ability to substantially reduce road congestion), whilst offering the user a service quality akin to a private car but without traffic congestion.

## **VI. Description of MISTER**

Conceived in 2005 (when the first patents were filed), the Metropolitan Individual System of Transportation on Elevated Rail (MISTER) is a Personal Rapid Transit (PRT) system. Demonstrated by means of a 1:1 working prototype in Opole in 2007, MISTER subsequently underwent comprehensive technical and economic due diligence, being awarded a European High Technology Grant. As described by Mikosza<sup>15,16</sup> and Lambo<sup>17</sup>, MISTER has inter alia the following characteristics:

- Lightweight vehicles (300kg “pods”) suspended from an unobtrusive guideway suspended 8-15m above ground level.
- Can ascend or descend 45 degrees, with a 3 metre radius turning circle, so can be accommodated into almost all existing urban environments.
- Each pod can accommodate up to 5 persons or two both with bicycles.
- Street-level boarding with level floor, so accessible for the mobility impaired.
- No ride-sharing with strangers.
- Vehicles individually electric-powered via ‘third’ rail located within the guideway.
- Travel direct-to-destination (no intermediate stops) at 50-70kph; vehicles stop offline.
- Patented guideway switching ensures fail-safe operation.
- Easy, modular system expansion capabilities.
- Minimal footprint for guideway (equivalent to a lightpole’s footprint).
- Significantly reduced construction costs: US\$7-10m per km (two-way track, including stops and pods).
- Specialised pods for freight delivery, with a capacity of up to 400kg per pod.
- Can be installed at the rate of one km per month in each direction.

## **VII. Summary Results from Modelling: Opole, Poland**

### **• Opole and Data Sources**

Opole is a city and provincial capital in Poland with a resident population of around 146,000 people, including a significant number of tertiary students. In 2007, MISTER exhibited a 1:1 working prototype of their PRT system in the city; and also received approval to implement MISTER in the city, subject to raising finance to proceed. Demographic, land use, and economic data (historic, existing, and forecast) were obtained from a number of sources<sup>18,19,20,21</sup>. Data on existing public transport services were obtained from operators<sup>22,23</sup>. Traffic counts and travel diaries were not available, but calibrated traffic levels and speeds, were reviewed and checked by the co-author (then resident in Opole).

### **• Outline of Modelling**

In order to enable detailed consideration of the MISTER network (with stops spaced more closely than train or bus stops), a detailed zoning system was developed, comprising 917 zones. Transport networks were coded to a corresponding level of detail. The model was developed using EMME. Binary mode choice was used between car using and noncar using (i.e. public transport: bus, train, walk, and in future scenarios, PRT). EMME's transit assignment algorithm was used to analyse routeings for public transport, rather than using submode split, as it is quite conceivable that PRT passengers could use bus or train for access/ egress. The forecast horizon adopted was 2050, with AM Peak, Inter-Peak, and PM Peak periods modelled separately. A 32.6km network of MISTER PRT was coded into EMME and tested.

- **Key Assumptions**

Population forecasts were based on data from Opole City<sup>21</sup>. Trip rates were based on Jastrzębski<sup>24</sup> and Fouquet<sup>25</sup>, taking account of income levels from Eurostat<sup>20</sup>. MISTER fare levels were assumed to be 3.40 Zloty (US\$1) for boarding plus 0.34 Zloty per km (pro rataed).

System certification was assumed to cost US\$30m and to take 18 months. Depot and control centre construction would cost US\$15m and take 6 months, concurrent with the 7 month construction of the first (8.4km) phase of MISTER. Track was costed at US\$8m per km for two-way track, including stops and pods (100 pods per km of two-way track). The second phase is 9.1km (5 months to construct); the third phase is 9.0km (4 months to construct); and phase four is 6.2km (3 months to construct). Demand ramp-up of 50% over 6 months was assumed. Based on MISTER's detailed project plans (consistent with those used for EU due diligence): a pod occupancy of 1.5 was assumed (similar to car occupancies), with annual servicing per pod costing US\$1,030. Pods travel at 55kph, using 5kW of power (US\$0.10 per kW). 20% of deadheading pod kilometrage was assumed to allow for pods to match demand. MISTER staffing was assumed to be 20 plus 5 per km of two-way track (ZL70,000/ US\$20,588 per person per year).

- **Preliminary Modelling Outputs**

For space reasons, modelling results herein are confined to summary results from preliminary year 2020 forecasts. The 32.6km MISTER network would, on a daily basis:

- Increase noncar (i.e. bus, train, walk, PRT) mode share from 12% to 32%.
- Give overall journey time savings for car users of 11% per trip.
- Decrease overall fuel consumption by 21.6% citywide.
- Generate almost 153,000 boardings per day on MISTER, with over 450,000 passenger-km travelled.

These forecasts show not only the potential attractiveness of MISTER to users, but also that a MISTER PRT network would yield sizeable journey time savings for nonusers, through decongesting the city and so boosting mobility for all.

- **Internal Rate of Return (IRR)**

The Internal Rate of Return (IRR) for the project was calculated both including system certification (if this were the first MISTER roll-out in Europe), coming to 18.4%; and with certification excluded, yielding an IRR of 20.6%. These IRR's demonstrate that MISTER would be commercially viable without need for government subsidies, aside from access to the right of way (which as described previously does not require a large footprint). These

rates of return also show that there would be sufficient margin to entertain revenue sharing with potentially cash-strapped local authorities (or to cover sales taxes on tickets, were such levied).

### VIII. Conclusion

Any true next generation transport infrastructure must be cheaper and offer a vastly improved level of service relative to existing technologies. Such infrastructures should axiomatically sustain the mobility and development of modern communities (ideally being more environmentally friendly to both construct and operate). MISTER Personal Rapid Transit has been shown to require substantially less capital and operating expenditure than last generation systems. Indeed, besides access to right of way, public subsidies should be unnecessary. It is potentially highly attractive to users, overcoming many of the problems faced by orthodox public transport; this also results in wider decongestion and environmental benefits, increasing mobility for all and therefore assisting the sustainable development of modern communities. Moreover, MISTER PRT projects should offer attractive returns to investors.

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# Structuring Socio-Technical Complexity In Infrastructure Systems: The Biogas System

Reinier Verhoog<sup>a</sup>  
Amineh Ghorbani<sup>b</sup>  
Gerard P.J. Dijkema<sup>c</sup>  
Margot P.C. Weijnen<sup>b,\*</sup>

**Abstract:** Infrastructure systems consist of many heterogeneous decision making entities and technological artefacts. They are governed through public policy that unravels in a multi-scale institutional context, ranging from norms and values to technical standards. For example, to integrate biogas infrastructure in a region, various forms of governance, laws and regulations need to be implemented. To effectively design these requirements, insights into socio-technical systems can be gained through agent-based modelling and simulation. To implement such social concepts in agent-based models of infrastructure systems, we designed a modelling framework called MAIA, based on the Institutional Analysis and Development framework of Elinor Ostrom. This paper will explain how MAIA can be used to model a biogas energy infrastructure in the Netherlands.

**Key words:** Agent-based modelling; Social simulation; Institutional analysis; Conceptualization.

## I. Introduction

Many of the infrastructures that we see today find their origin in simple and often local physical assets, governance, laws and regulation. In the early 20th century, electricity grids in the Netherlands started off as local grids, referred to as islands since they were often not connected, which were governed by the local municipality and Grid Company. As technology advances, infrastructures grow in size and become increasingly interconnected, the robustness of these systems increases but also their complexity. Infrastructure systems are not static, but rather in a state of constant evolution as perceptions and goals of the stakeholders change which are translated to new policies<sup>1</sup>. Policy decisions drive the evolution of the infrastructures, which can be seen to be subject to a constant pressure for change to meet ever shifting perceptions and goals. An example of this is the goal to reduce CO<sub>2</sub> emissions and increase renewable energy production. Centralized fossil based energy infrastructures were not initially designed with these goals in mind and are being changed to allow for decentralized renewable energy production for example. It is the continuous interplay between the innovation of the physical infrastructure and the stakeholders through policy and system performance that makes infrastructures complex socio-technical systems.

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<sup>a</sup> Chair Management of Network Industries, College of Management of Technology, EPFL, CH

<sup>b</sup> Energy & Industry group, Faculty of Technology, Policy & Management, Delft University of Technology, NL.

<sup>c</sup> Chair Energy Systems and Industrial Ecology, Energy and Sustainability Research Institute Groningen, Groningen University, NL

\*Corresponding author: Margot Weijnen (weijnen@tudelft.nl)

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Agent Based Modelling can be used to model long time periods, just like the popular Equation-Based Models<sup>2</sup>. This is ideal for modelling transitions in systems characterized by a certain degree of inertia and path-dependency as can be expected from (established) infrastructures. To determine whether Agent Based Modelling is a suitable means to model infrastructure systems, van Dam (2009) provides three conditions for complex systems<sup>3</sup>. All three conditions hold for infrastructures:

- Distributed character: stakeholders are interdependent for the realization, operation and utilization of the infrastructures, but are also autonomous in the sense that they can make their own decisions.
- Highly dynamic environment: infrastructure policy and regulation is constantly changing because of shifts in perceptions and goals of stakeholders. Infrastructures are also affected by global trends.
- Interaction flexibility: interaction between stakeholders is not fixed as there are numerous issues that require the attention of multiple stakeholders and there is often not a standard solution.

Any modelling exercise is limited in its focus and level of detail since clear boundaries have to be defined and assumptions have to be made to keep the required efforts within acceptable limits. Therefore, the Agent Based Modelling exercise should be viewed as a process of learning and exploring rather than finding the complete answer<sup>4</sup>.

Apart from learning, conceptual modelling is useful in the process of creating an Agent Based Model. First, conceptual modelling bridges the gap between the real world system and the Agent Based Model, which make it easier and more effective to communicate to others, including those without actual modelling experience. Second, performing the conceptualization step-by-step allows for dialogue between modellers and experts at earlier stages in the process. Third, investing time in conceptualization can result in significant time savings later on in the process. Reaching consensus amongst modelling collaborators as well as unambiguity of the (conceptual) model is important to prevent conflicts and time-consuming model alterations down the road<sup>5</sup>. Finally, because of the richer dialogue and more effective communication, conceptual modelling increases learning.

In this paper MAIA, a meta-model for agent-based modelling of socio-technical systems<sup>6</sup>, will be applied to conceptualize an agent based model of a biogas infrastructure system in the Netherlands and to demonstrate the applicability of MAIA to infrastructure systems. MAIA is useful for modelling infrastructure systems as it not only puts emphasis on the stakeholders and physical artefacts, but also the policies, regulation and governance of the infrastructure system. A static description would not serve much purpose as socio-technical systems are inherently evolutionary due to changing stakeholder perceptions and goals. MAIA provides a clear structuring of agent actions which detail the interactions and outcomes necessary to simulate the evolution of an infrastructure system.

While the biogas infrastructure in the Netherlands is small, it is currently developing at a fast rate compared to the natural gas and electricity infrastructure in the Netherlands. Biogas production by water treatments as well as agricultural firms has seen an increase in recent years, as well as the applications of biogas. Biogas is often converted to electricity or upgraded to green gas quality, but it can also be used directly with specialized equipment to replace natural gas. To allow for the production and utilization of biogas in these different

applications, the biogas infrastructure is often connected to existing infrastructure, which increases the amount of stakeholders and physical artefacts. Biogas infrastructure is therefore a complex socio-technical system that may exhibit large evolutionary steps in the years ahead.

## **II. Modelling Agent Systems Using Institutional Analysis**

MAIA is based on the Institutional Analysis and Development framework (IAD)<sup>7</sup>. MAIA extends and formalizes the IAD concepts to facilitate automatic translation of a systems description to executable software<sup>6</sup>. The MAIA meta-model consists of the following five interrelated structures<sup>6</sup>:

- Collective structure. Stakeholders are translated into agents by capturing their characteristics and decision criterion based on their perceptions and goals.
- Constitutional structure. Stakeholders can perform multiple roles in infrastructure systems. These roles are formalized in the constitutional structure and have clear rules on who is allowed to perform a certain role. Different roles have different objectives and capabilities, which allows easy modeling of heterogeneous agents who perform similar tasks.
- Physical structure. Physical artefacts are required to produce, convert, transport and consume goods and together make up the physical infrastructure. Stakeholders (agents) own different parts of the physical infrastructure and their assets can either be open to everyone or only accessible to them.
- Operational structure. Stakeholder interactions and decision making are important since they shape the infrastructure system and determine the systems performance. Stakeholders interact in the action arena which consists of several action situations where stakeholders perform actions, affected by the system status over time, powers shift and perceptions change.
- Evaluative structure. Agent interaction and system performance are measured and evaluated. Depending on the perspective of the observer the criteria used to evaluate the infrastructure system under study can vary.

## **III. The Biogas Infrastructure**

With an estimated 60PJ in 2030, the theoretical potential for biogas production in the Netherlands is substantial<sup>8</sup>. However, most of the potential is based on the production of biogas by farmers, many of whom are currently struggling to earn back their investments. Subsidies play an important role to render the operation of biogas production economically viable in the Netherlands<sup>9</sup>.

Currently, biogas infrastructure and production is relatively small in the Netherlands, but it cannot be seen as an entirely separate infrastructure. Rather, the biogas infrastructure is linked to the electricity infrastructure and to the natural gas infrastructure. This makes biogas an interesting case to study from an institutional point of view, because it brings together the as yet unregulated biogas domain with the electricity and natural gas domains that are subject to extensive regulation.

#### **IV. Modelling the Biogas Infrastructure**

We use the MAIA structures to conceptualize the biogas system. Due to space limitation we will not go into the details of the model here but we will only provide an overview of the concepts for each action situation in the model. The modelling exercise focuses on the production of biogas by water treatments and agricultural firms in the Netherlands and the direct usage of the produced biogas by the consumer.

##### **E. Collaboration Action Situation: finding partners to reduce biogas project costs**

Biogas production and consumption is location dependent because of the transportation and infrastructure costs over longer distances are prohibitive. Economies of scale play an important role in controlling the investment and operation costs of biogas production artefacts. For this reason, farmers defined as agents will attempt to collaborate to share investment costs. The internal decision is simple: if a farmer is interested in biogas production, if its firm is located sufficiently nearby and if the production of biogas is technically feasible for all farmers' firms involved, the farmers will collaborate. Their firms will not merge, as the collaboration only relates to the biogas projects.

##### **XXII. Biogas contract negotiations action situation: setting a quantity and price for biogas production**

The model focuses on the amount of biogas production as well as the economic performance of biogas producers. Generally, water treatment plants perform well economically as they can produce biogas at a cost as low as 0.037 [€/Nm<sup>3</sup>]<sup>10</sup>. The internal decision model for the biogas producer is mainly based on the expected fixed costs and operational costs of biogas production. The internal decision model for the energy consumer is based on the value of natural gas and the reduction of CO<sub>2</sub> emissions by consuming the biogas instead of natural gas. This means that the value of biogas is different for households than it is for large industrial consumers. The agreement is made for a long period of time (at least 12 years) to cover the economic lifetime of the biogas production artefacts.

Once a quantity and price is agreed upon by the producer and consumer (defined as a role in MAIA), it is assumed that all the necessary permits are granted and that the physical artefacts become available for biogas production in the next year. This is a very simplified take on reality, as permits can be a real limitation in some cases when the perception of biogas production is not positive.

##### **XXIII. Biogas operation action situation: maximizing operational profit**

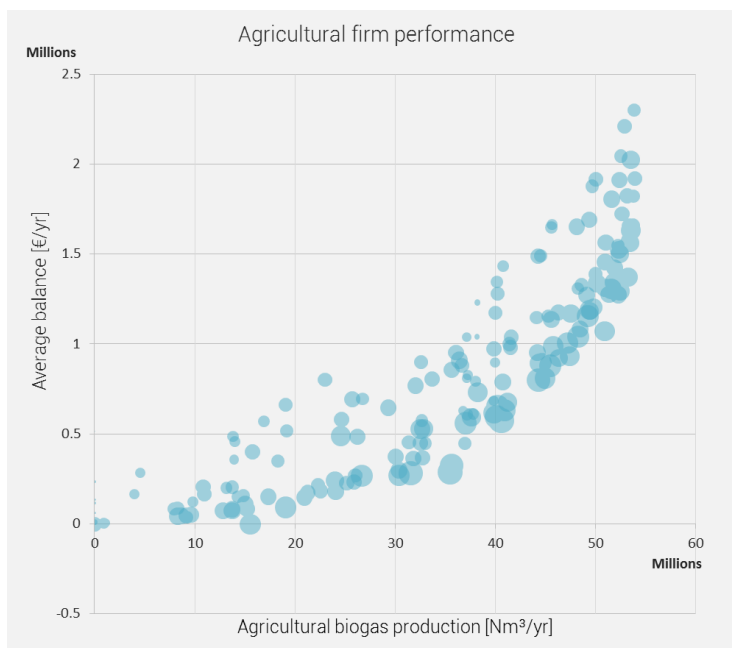
The operation of biogas production artefacts is driven by the operational costs and expected profits only. Fixed costs are incurred no matter what the biogas producer does. Water treatment plants have access to a constant and free feedstock, so they will always make an operational profit for the duration of their contracts. Agricultural firms are really dependent on the changes of co-substrate prices, natural gas prices and CO<sub>2</sub> prices. Co-substrate prices are very volatile and can result in large operational losses (or profits) for agricultural firms. Start-up costs of biogas production assets are very high as well, which means that not producing any biogas is often not an option either.

#### **V. Simulation results**

A The conceptual MAIA model was used to build an agent-based simulation. To build the simulation, data has been collected for different parts of the model. First, the model's

performance in terms of agricultural biogas production and balance is very sensitive to the market prices of co-substrate, natural gas and CO<sub>2</sub>. This means that the performance is largely determined by external forces. The model is also sensitive to the write-off period and whether or not prices can be renegotiated during the contracted period. These are negotiation issues that can be determined by the agricultural firms and consumers, therefore these parameters are internal.

Second, it can be observed from figure 1 that the performance of agricultural firms is acceptable to good in almost all 240 scenarios for which the model was run. Risks of individual agricultural firms earning back their investments are shown as the size of the bubbles in figure 1. The risks range from 0% risk to 3.15% with an average of 0.92% over all scenarios.



**Figure 1. Agricultural firm performance.** The size of the bubble indicates the risk of an individual agricultural firm, which ranges from 0% to 3.15%, with an average of 0.92% for all 240 scenarios.

Third, the banana shape indicates that under favourable conditions the agricultural firms do not only produce more biogas but also earn more on the produced biogas. This can be explained by the fact that competition was not directly taken into account in the model in the sense that it could influence the price of biogas.

Fourth, agricultural firms can only compete for the quantity of biogas that is produced, which is limited by the total demand in the simulated area. This explains the asymptote at around 54 million [Nm<sup>3</sup>/yr].

## VI. Conclusion and Future Work

Conceptualization using MAIA offers sufficient completeness and a sufficient level of detail to allow even modellers without any domain specific knowledge to implement a simulation model. The conceptual model should be created with scientific rigor, for which the

five MAIA structures can be used to efficiently gather the required knowledge and data. Special attention should be paid to internal decision models and agent actions at the smallest scale to ensure that the formal description is as close to the simulation model implementation as possible. The online MAIA tool can be used to structure the data in cards and exchange it with other modellers or programmers to extend or implement the model.

The conceptual biogas model has been implemented by different modellers. One model is implemented using NetLogo and the other model is implemented using Agentscape. Both model implementations were solely based on the conceptual biogas model and did not use additional conceptual models. The models have not been compared yet in terms of structure or model output. Future work will focus on the comparison of the two model implementations.

### Acknowledgements

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# What Makes a City Liveable? Implications For Next-Generation Infrastructure Services

J.M. Leach<sup>a\*</sup>  
S.E. Lee<sup>a</sup>  
P.A. Braithwaite<sup>a</sup>  
C.J. Bouch<sup>a</sup>  
N. Grayson<sup>b</sup>  
C.D.F. Rogers<sup>a</sup>

**Abstract:** Infrastructure forms the framework within which modern societies operate both at the physical and social level. It includes (amongst others) digital, green and social infrastructures, emergency services and food networks, water, energy, waste and transport. Infrastructure, by its very nature, locks in behaviours. The Liveable Cities research consortium aims to identify and test radical engineering interventions that will lead to future low carbon, resource secure cities in which societal wellbeing is prioritised, and these will necessarily influence the shape of infrastructure provision. This paper presents a discussion of what comprises a liveable city and how it might be achieved. It presents the City Design Framework, a technique for the analysis of city strategies that establishes a hierarchy of needs relevant to successfully achieving a liveable city. The framework supports changing perceptions of infrastructure since the necessary future changes have the potential to radically alter people's lifestyle and wellbeing.

**Key words:** Liveability; Liveable city; Sustainability; City design; Strategic management; Infrastructure planning; Performance parameters.

## I. Introduction

Cities need to be sustainable, which broadly means living within what the biosphere can provide and (in terms of wastes and emissions) absorbing without overburdening future natural resources, and resilient, in that it continues to function in the face of (radical) change. Moreover, wellbeing and quality of life is highly valued and should be ensured for all in the future. The adjective increasingly used to capture these aspirations is 'liveable'. The world is facing considerable challenges in realising these liveable aspirations and it is widely accepted that there is an imperative to act quickly if even more serious consequences are to be avoided in the future – current ways of living are already storing up serious future consequences. Accordingly, Liveable Cities, a 5-year research programme, combining the Universities of Birmingham, Lancaster, Southampton and University College London (UCL) and funded by

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<sup>a</sup> Civil Engineering, University of Birmingham, Birmingham, B15 2TT.

<sup>b</sup> Birmingham City Council, Birmingham, B1 1BR, UK.

\*Corresponding author: Joanne Leach [j.leach@bham.ac.uk](mailto:j.leach@bham.ac.uk)

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the Engineering and Physical Sciences Research Council (EPSRC), was established in 2012 to identify and test radical engineering interventions that will lead to liveable cities of the future. The focus of this programme concerns pathways to low-carbon, resource-secure cities in which societal wellbeing is prioritised, while changes in population, demography, climate, security of energy/other resources, and a plethora of historical legacies, provide the context<sup>1</sup>.

In order to bring about appropriate changes, it is important first to understand how cities function and how well they perform. This provides a baseline against which to identify and prioritise aspects that would benefit from change and assess the impact of interventions. Accepting that cities are enormously complex and individual in nature, there is a need nevertheless to establish a framework in which the most important indicators of functional performance can be described and assessed. The approach taken by Liveable Cities, and reported herein, is to view cities through a comprehensive set of different disciplinary lenses covering social, environmental and economic perspectives, distil from these views sets of performance parameters that describe how cities and their citizens operate, and capture them in a bespoke framework. The framework adopted is derived from a classical strategic framework that links visions through aims and objectives, and then strategies and policies, to processes and actions – a City Design Framework (CDF). This can then be applied to any city and its context by analysing its visions, formal and informal policies, strategy documents, de facto strategies and practices to fill in the gaps in the framework and then, via datasets and models, explore its performance both before and after interventions. While this process is conceptually straightforward, the implementation of change relies upon a fit to the context, exogenous and endogenous influences and city capacity and capability, and faces many barriers, such as resistance to individual and societal behaviour change, political will to enact change in a climate of short-term electoral cycles, professional inertia, the capability and capacity to effect changes and the perceived risks associated with doing things differently. Nevertheless it has the potential to make explicit the opportunities and consequences of action or inaction.

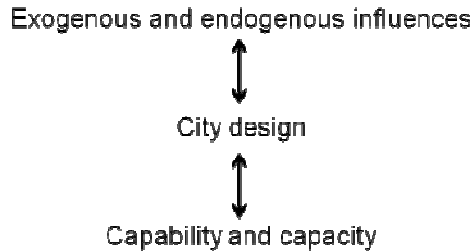
## **II. What is urban liveability?**

Dictionary and thesaurus definitions of liveability indicate that liveability is about being suitable for (usually) human living<sup>2,3,4,5</sup>. These definitions suggest a basic level of suitability, tolerability and functionality that is at increasing odds with the use of the word when applied to cities. In relation to cities, liveability describes the surpassing of basic living conditions to meet aspirations. This is reflected in the annual rankings of liveable cities by (separately) the Economist's Intelligence Unit, Mercer and Monocle<sup>6,7,8</sup>.

This paper is concerned with the liveability of cities from the UK perspective and how centres of population can be developed to ensure improved liveability. Infrastructure provides the structures and mechanisms through which cities function at their most basic: energy water, waste, etc. Infrastructure also provides the structures and mechanisms through which cities function at their most sophisticated: ICT, integrated public transport, low carbon energy, re-use and recycling, sustainable communities, etc. Thus infrastructure is crucial in achieving urban liveability.

Liveability is almost inextricably linked to the sustainability of cities. In fact, Portney<sup>9</sup> maintains that, as concepts, liveability and sustainability are practically indistinguishable. In practice, however, a sustainable city is not de-facto liveable and a liveable city is not de-facto sustainable. Despite, or perhaps because of, extensive writings and reflections on

sustainability and liveability their meanings remain, as they did at the time of Portney's writing, nebulous and open to a myriad of interpretations. This paper proposes that liveability and sustainability can, and should, be inextricably intertwined, incorporating societal and planetary wellbeing within the context of low carbon living and resource security.



**Figure 1. Influences upon city design, adapted from Foundation for Global Education and Research<sup>17</sup>**

### **III. Factors to Consider when Designing a Liveable City**

This paper proposes a framework that allows cities to design for liveability as defined above (perhaps best termed a 'common challenge') whilst at the same time addressing bespoke challenges specific to themselves (often arising from their local context). Cities must be cognisant of and responsive to exogenous and endogenous influences (including global trends such as climate change, systemic rules such as governance systems and available resources such as natural capital), and its own capabilities and capacities (see Figure 1). Cities are bespoke entities, closely coupled to their immediate surroundings. One-size-fits-all solutions are not an option.

#### ***A Framework for Designing a Liveable City***

It is convenient to think of the city design process in three stages:

- 1) Knowing what the city wants to be like in the future
- 2) Knowing what the city is like now
- 3) Knowing how to get from how the city is now to how it wants to be in the future

#### ***Knowing what the city wants to be like in the future:***

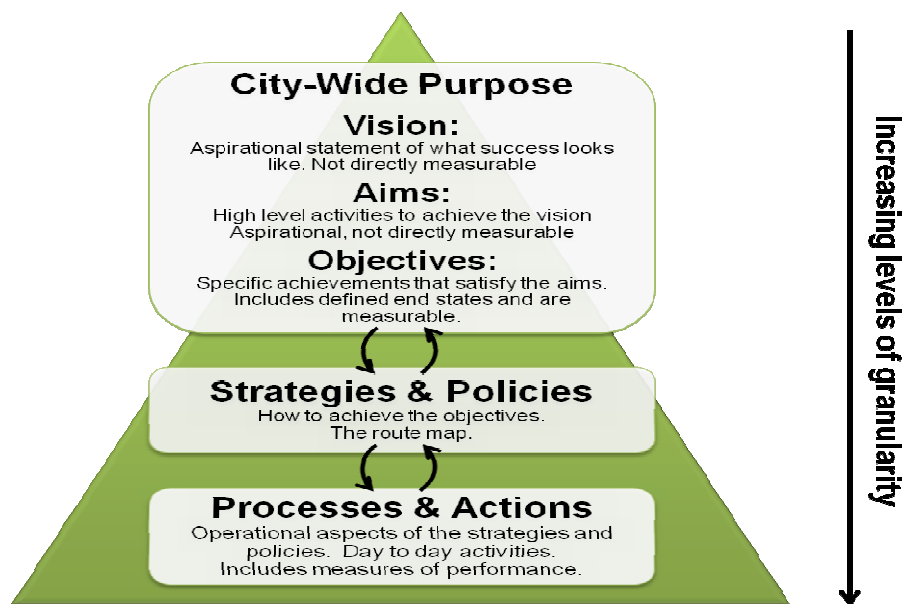
Envisioning the future is no easy feat, not least because the only certainty is that all predictions of what the future will be like will, in one respect or another, be wrong. Once a vision for a city's future has been agreed it must be put into operation. The strategic management literature provides a useful approach. The strategic management hierarchy<sup>10,11</sup> is represented by a triangle that is horizontally sliced into discrete sections that increasingly deconstruct a vision. Figure 2 describes a strategic management hierarchy for a single city. Each layer reflects a level of decision-making, deconstructs the layer above, feeds the layer below and provides feedback for the layer above.

The 'city-wide purpose' comprises the city's vision, aims and objectives and considers the city as a whole unit. The city's vision statement is at the top, of the triangle and is the least

detailed element. A vision statement is a high-level, aspirational statement of what success looks like. It is not, and should not be, measurable<sup>12</sup>. Many cities will, in fact, have multiple (or multi-part) visions of the future, which may or may not be mutually supportive or cohesive. For example, the vision to be economically vibrant with a focus on advanced manufacturing may well render a low carbon vision difficult and potentially introduce additional barriers to liveability beyond those currently in existence.

This paper proposes the following vision for a liveable UK city: it will be a low carbon, sustainable city providing the highest quality of life with the highest resource security. The vision is deconstructed into a handful of aims: statements that elucidate the core elements of the vision. Aims are the high-level activities that will achieve the vision and, like the vision, are not directly measurable. With regard to liveability, suitable aims for a UK city would be:

- Minimise operational and embodied carbon
- Be resource secure
- Maximise individual and community wellbeing
- Maximise ecosystem services
- Be economically viable



**Figure 2. City Strategic Management Hierarchy adapted from Bordum<sup>10</sup> and Bititci, Carrie and McDevitt<sup>11</sup>**

Each aim is further deconstructed into objectives that contribute directly to the success of a particular aim. Given that cities work across departments on programs, objectives can be 'less SMART': less specific, less measurable and less accurately timed, but still achievable and realistic<sup>13</sup>. There should be enough objectives to address all priority elements of each aim, but not so numerous that they become unwieldy. For the aim of minimising operational and embodied carbon suitable objectives might be:

- Reduce energy use from carbon fuels by 80% (from 1990 levels) by 2050
- Reduce potable water use to 60 liters per person per day by 2050
- Eradicate solid waste to landfill so all solid waste is re-used or recycled by 2050

The relationship between aims and objectives can be ‘first order’, meaning that any given objective contributes directly to the achievement of its related aim. The objective may also contribute indirectly (a second order relationship) to other aims, but its primary purpose is to achieve its related aim. First order relationships form a critical path to success.



**Figure 3. City Design Framework**

Following the hierarchy down to the next level sees the development of strategies and policies to achieve the objectives. It is as important at this level as it was at the objectives level to ensure that first order relationships exist between the strategies and policies and the objectives. Second and even third order relationships should also exist. Together with the first order relationships they form a network of activities that increases the overall resilience of the strategic management hierarchy as well as of any one strategy or policy. Indeed, a network approach should be repeated throughout the hierarchy for this very reason.

Strategies and policies are the statements of how to achieve the objectives. They provide a level of detail that is sufficient to understand the important aspects, end states and targets required achieving each outcome without becoming mired in the operational detail of the day-to-day processes and actions required, which is reserved for the next level of the hierarchy: processes and actions.

Performance measures at the operational level (processes and actions) must be SMART: specific, measurable, achievable, realistic, and timelined<sup>13</sup>. They should consist of two elements: (1) movement towards achieving the stated targets and (2) understanding the city's functions. Indicators are useful, and frequently used, to measure performance. Indicators alone, however, are not sufficient to understand how a city is actually functioning. What is required is a deeper understanding of operations, which can be achieved through material and energy flow analyses. It is here that the intended and unintended consequences of activities at each level of the hierarchy upon the workings of the city can be elucidated.

The City Strategic Management Hierarchy (Figure 2) can now be brought together with the influences upon city design (Figure 1) to form a framework for city design (Figure 3).

### ***Knowing what the city is like now:***

Success is dependent upon the city having a clear understanding of where it is now so that it can align its current design to its desired design (in this case a design for liveability). This alignment should take place as quickly as possible so that all future activity can be put into moving the city towards its long-term liveable vision. In practice, however, it will be necessary to accept that some policies, strategies or activities that do not fit the overall vision will need to be accommodated for various reasons, for example they may be political, reactionary or urgently required interventions. Such policies, strategies and activities need to be recognised as outside the liveable city vision and invested in appropriately in terms of money, associated disruption and lifespan of the intervention.

### ***Knowing how to get from how the city is now to how it wants to be in the future:***

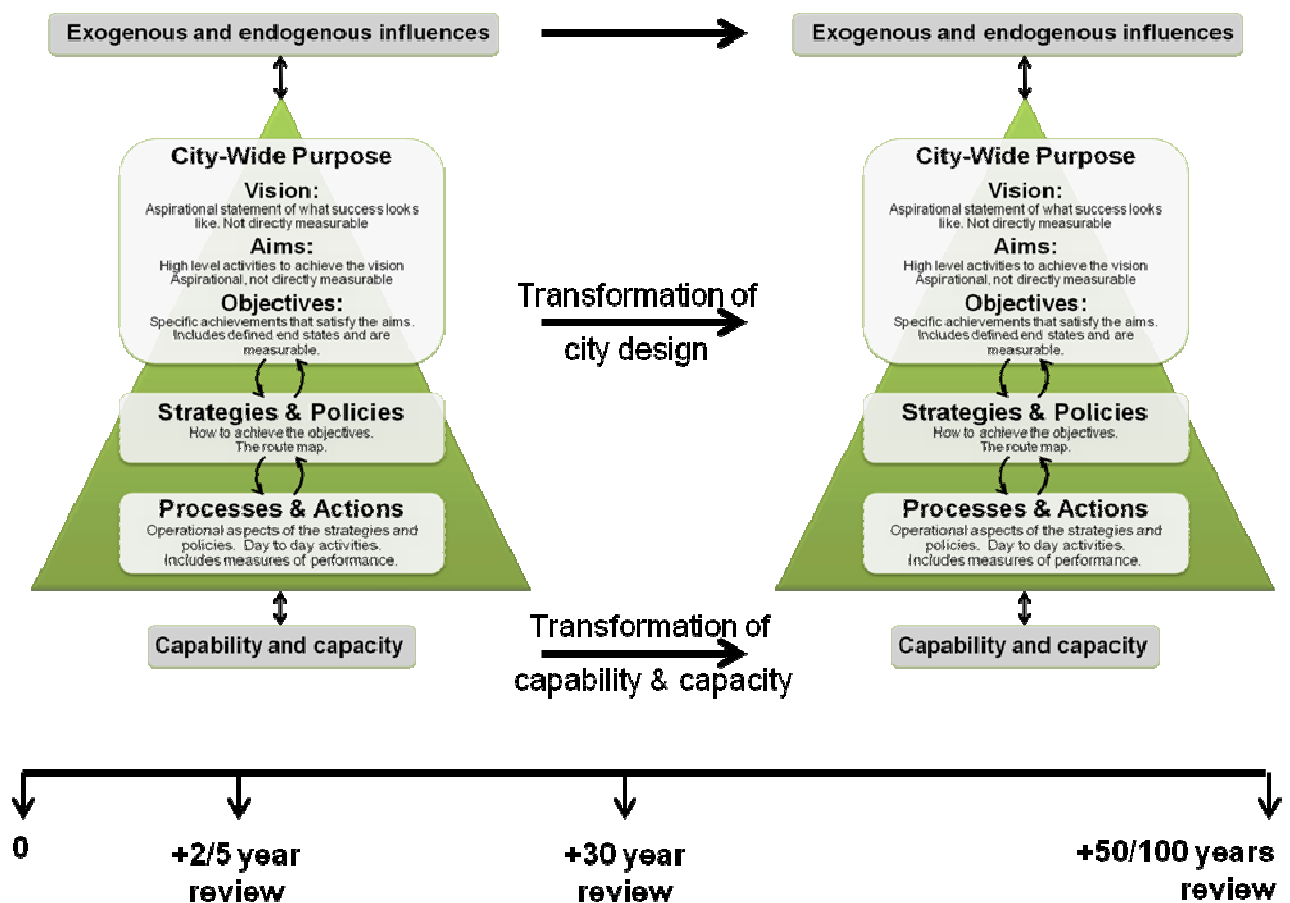
Over time strategies and policies and processes and actions will need to be reviewed and revised to accommodate progress towards the vision and changing contexts. The rate of change depends upon the nature of the element in question. Some infrastructure, such as housing stock, roads and rail can be in place for more than 100 years. Other infrastructure, such as high speed fiber optics, may not be relevant for more than five years. In this context it might be helpful to define timescales: short-term (two to five years), medium-term (30 years) and long-term (50 to 100 years). Figure 4 illustrates these time horizons as applied to the City Design Framework, forming the basis for a roadmap.

## **IV. Implications for Infrastructure**

Infrastructure can be defined in a variety of ways. In the UK infrastructure is generally agreed to include energy, water, communications, transportation and waste. The Cabinet Office<sup>14</sup> lists nine sectors of UK infrastructure (each having sub-sectors): energy (including heat networks), water (including water resources and flood defense), communications, transportation, food, emergency services, health care, financial services and government. This services conception of infrastructure can be broadened again to incorporate a systems approach that includes: interdependencies, the effect of the quality of infrastructure upon the national offering (how much more attractive is the UK if it has good infrastructure), societal impacts and green infrastructure that delivers ecosystem services. However it is in this statement that conflict of scales becomes apparent, since infrastructure is conceived variously

at an international, national, regional, city and sub-city scale; for a city it is a question of those that are wholly contained plus linkages to beyond city boundaries.

Infrastructure underpins urban liveability, where liveability is defined as societal and planetary wellbeing within the context of low carbon living and resource security. It does this in well-understood ways, providing the structures and mechanisms required for a city to function (see the above lists of resources and other services). Infrastructure also underpins liveability in less well understood ways by providing the building blocks upon which cities flourish. Perhaps the best example of this is the building of the London sewers that led to improved urban environment and citizen health, making London a highly desirable place to live and conduct business and arguably enabling it to become the mega-city it is today<sup>15</sup>; it would be possible to capture this in the CDF. More problematic is the current debate in England about the viability of the proposed High Speed 2 (HS2) rail link connecting London with the Midlands (Birmingham) and eventually the North of England (Manchester and Leeds). It is proving difficult to make the business case precisely because the full effects of the investment are unknown<sup>16</sup>, and when applying the CDF it is just as difficult to know where to allocate the benefits and disbenefits of such a scheme; in short, will they concentrate in London, the southeast more generally, the three regional cities or the UK more generally. This argument extends to all other aspects of the performance of a city, meaning that the parameters vary both temporally and spatially and boundaries of influence are difficult to draw.



**Figure 4. City Design Framework Roadmap, adapted from Foundation for Global Education and Research<sup>17</sup>**

## V. Conclusion

This paper has described a framework for measuring the performance of a city and enabling the impact of interventions to be deduced. In turn, it provides a roadmap (or at least the means to create a roadmap) for improving the planning of infrastructure (and other) investments for the purpose of creating liveable cities. Further research is on-going to understand the full economic, social and environmental effects of infrastructure investments, and where their impacts lay both spatially and temporally. The aid to planning lies in informing the city's exogenous and endogenous influences, the various levels of the City Strategic Management Hierarchy (and the first, second and third order relationships that connect them), the city's capabilities and capacities, as well as how these will change over time. Moreover, in addition to strengthening the linkages upwards and downwards in the space between vision and processes and actions, it provides a vehicle to explore the potential impacts, both positive and negative, of radical change and provide a very real possibility that it might be adopted where the benefits outweigh the disbenefits.

## Acknowledgements

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# A Probabilistic Predictive Model for Residential Mobility in Australia

M. Namazi-Rad<sup>a\*</sup>

N. Shukla<sup>a</sup>

A. Munoz<sup>b</sup>

P. Mokhtarian<sup>c</sup>

J. Ma<sup>a</sup>

**Abstract:** Household relocation modelling is an integral part of the planning process as residential movements influence the demand for community facilities and services. Department of Families, Housing, Community Services and Indigenous Affairs (FaHCSIA) created the Household, Income and Labour Dynamics in Australia (HILDA) program to collect reliable longitudinal data on family and household dynamics. Socio-demographic information (such as general health situation and well-being, lifestyle changes, residential mobility, income and welfare dynamics, and labour market dynamics) is collected from the sampled individuals and households. The data shows that approximately 17% of Australian households and 13% of couple families in the HILDA sample relocate residence each year. Yet, little is known on how this information can be utilised to develop a predictive model of household relocation. This study links changes in employment status and household types to a reliable estimate of the residential relocation probability by developing a Logit model to explain the residential relocation in Sydney metropolitan area using the HILDA dataset.

**Key words:** HILDA; Household Relocation Modelling; Logit Model.

## I. Introduction

Household residential relocations are individual decisions that are influenced by and affect community makeup, and population levels in different ways across countries. Where populations choose to reside increases the uncertainty of public policy upon future government services demands. This uncertainty also decreases the reliability of traditional equilibrium based approaches to modelling population movements. Changes in household configurations, individual attributes, and community structures have strong influences on the quality and types of services governments are required to provide. Thus, planners are under increasing pressure to develop robust policies that govern which area receives what services and why. Traditionally, residential relocation has been modelled using aggregate forecasting techniques. However, the assumptions supporting these models can fail to apply to specific socio-demographic segments of a population, increasing the need to adopt more

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, NSW 2522, Australia,

<sup>b</sup> School of Management and Marketing, University of Wollongong, Wollongong, NSW, 2522, Australia

<sup>c</sup> School of Mathematics and Statistics, University of Wollongong, Wollongong, NSW 2522, Australia

\*Corresponding author: Mohammad-Reza Namazi-Rad [mohammad\\_namazi@uow.edu.au](mailto:mohammad_namazi@uow.edu.au)

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sophisticated, robust planning tools based on peer-reviewed research. Research developments are plentiful in areas such as social psychology<sup>1-2</sup>, demography<sup>3</sup>, epidemiology<sup>4</sup> and other social and behavioural sciences<sup>5-7</sup>. Robust models of residential relocation have the power to incorporate the more important factors that influence a geographical area's popular perception and value of available services.

Models of relocation typically require region-specific attributes to be well incorporated as cultural and local geography factors play a significant role in relocation decisions<sup>8</sup>. Examples include tenure at the current residential location and the perceived net benefit of relocation. In order to measure existing individual perceptions of social and environmental elements, Namazi-Rad et al.<sup>9</sup> grouped attributes of interest to the target population to six factors describing various aspects of liveability perception. The work yielded a linear additive model to calculate reliable estimates of area-specific liveability indices. The model used a Computer Assisted Telephone Interviewing (CATI) conducted in Sydney by the SMART Infrastructure Facility. The study also linked perceived liveability with residential relocation decisions at the household level. The intention being to provide a singular predicted state based on an analytical model and necessary assumptions to ensure, tractability. These assumptions typically include the treatment of populations as homogenous non-autonomous individuals, a contentious assumption as individual households are typically autonomous decision makers. To address the issue, new models must consider the households as individual autonomous entities, capable of evaluating and processing available information into preferences and instantiate relocation decisions if required. The premise that individual entity choice is the required output of the model necessitates a re-thinking of how planners perceive the populations affected by implemented policies from traditional econometric equilibrium modelling views of populations as aggregations of homogenous individuals, to that of populations as a collective of autonomous, heterogeneous entities.

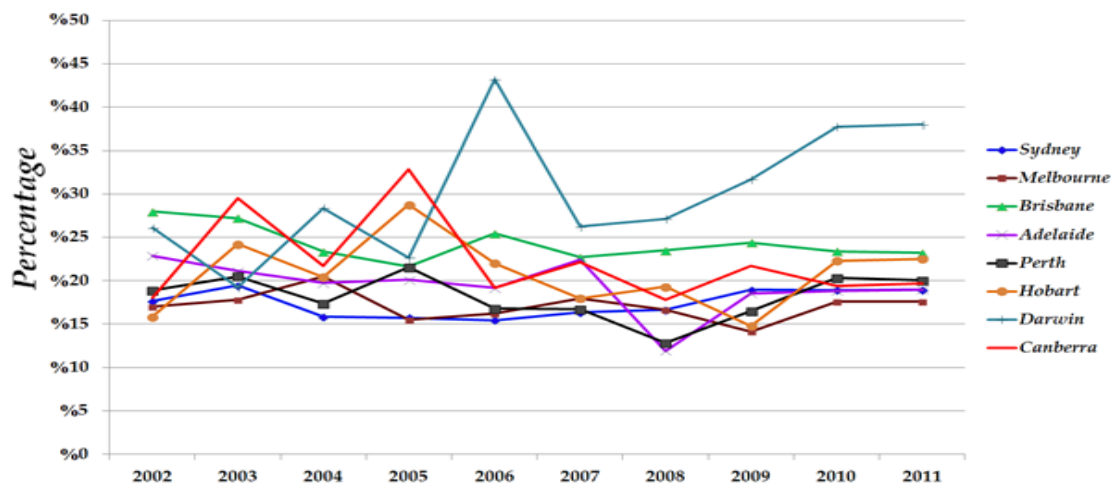
## **II. Modelling area-specific residential mobility based on HILDA**

Economic modelling has arguably been the only conceptually consistent and analytically tractable framework to model residential relocation dynamics. In the urban economics context, a willingness-to-pay driven framework relies on five axioms that to provide its consistency<sup>10</sup>: (1) prices adjust to achieve local equilibrium, (2) self-reinforcing effects generate extreme outcomes, (3) externalities cause inefficiency, (4) production is subject to economies of scale and (5) competition generates zero economic profit. This approach has been criticised by its reductionism, supported by arguments that residential relocation choices encompass factors like social bonding or 'sense of place' that can hardly fit into a single currency framework. Moreover, assumptions of perfect competition, economies of scale, and equilibrium markets tend to reduce the validity of conclusions inferred from such models. Louviere and Meyer<sup>11</sup> proposed to forge a better alliance between economic theories and behavioural research in order to improve our representation of informal choices within a discrete choice-modelling paradigm. A common methodology used in discrete choice modelling is Logit class models, whereby a number of alternatives are evaluated by the probability of each alternative being chosen by an individual autonomous entity.

This study will address the problem of modelling residential re-location using a Logit class model. The model estimates the probability of a household choosing to relocate and implicitly initiating the relocation process. Attributes contributing to the relocation decision include changes to number of bedrooms required, employment status and income situation, household configuration and tenure. The dataset used for the relocation choice model comes

from the Australian Government Department of Families, Housing, Community Services and Indigenous Affairs (FaHCSIA). FaHCSIA initiated the HILDA program to gather reliable longitudinal data on family and household dynamics. Socio-demographic information (such as general health situation and well-being, long term lifestyle changes, residential mobility, income and welfare dynamics, and labour market dynamics) is collected from the sampled individuals and households. The Melbourne Institute of Applied Economic and Social Research currently manage the HILDA project and the data repository.

Cursory data analysis indicates that around 17% of the total households and 13% of couple families in the HILDA sample relocate each year. Further analysis conducted shown in Figure 1, presenting the proportion of residential relocations in a year in Australian major metropolitan areas from 2001 to 2011. There are noticeable fluctuations in area-specific movements. For example, the proportion of movements in Darwin peaks in 2004-2005, perhaps due to the major development project initiatives in Darwin at the time: redevelopment of the Wharf Precinct and associated new housing developments, including Outrigger Pandanas and Evolution on Gardiner<sup>12</sup>. For Tasmania<sup>13</sup>, the influence of permanent migrants during 2004-2005 represented a significant increase of 141 residents from 2003-2004, and 278 more people than in 2002-2003.



**Figure 1. Self-reported movements within the Australian large cities**

The decrease in Canberra residents between 2003 and 2004 may be due to bushfire events. In January 2003 severe weather triggered catastrophic bushfires that destroyed around 500 homes. In reaction to the disaster, the Canberra Spatial Plan for the city's future development was released in 2004. Plans included a new Canberra district to be situated west of Lake Burley Griffin as initiatives to foster commercial and residential growth. Although the number of residential movements at the Australian major metropolitan areas has fluctuated from 2002 to 2011, on average the proportion of total households moved was between 17%

and 23% in 2011 except Darwin for which this proportion was approximately closer to 38%. Other objective and subjective factors not captured in this study would undoubtedly influence movements in different parts of Australia. The cursory analysis presented on Figure 1 represents some of the qualitative assessments of the model of residential relocation choice methodology will attempt to formalize.

### III. Residential location choice methodology

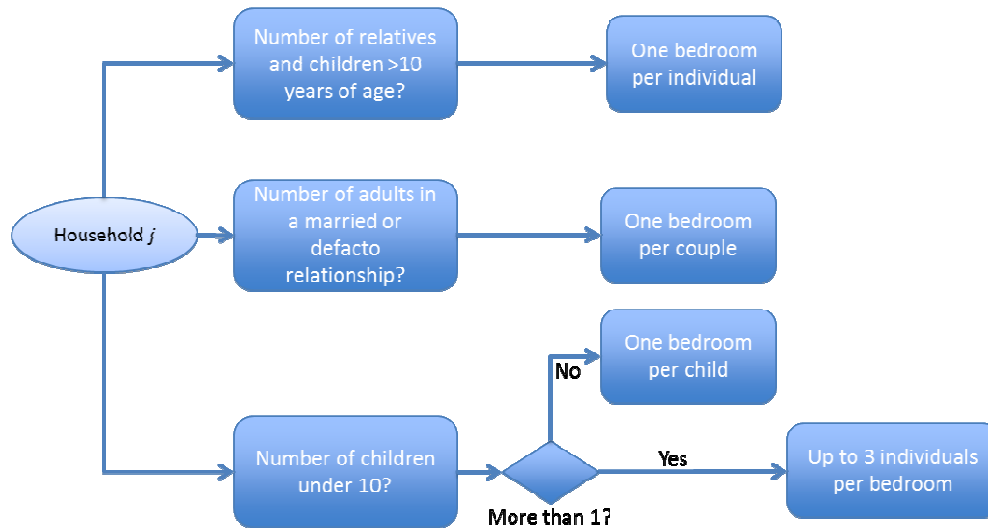
The purpose of this study is to determine if and when a household (at the Sydney metropolitan area) initiates the relocation process. It is assumed that all households are able to initiate the relocation process, whether the relevant conditions sufficiently necessitate the initiation of the process is the result of the model. For example, a household may be in a situation whereby a change in job location may require a longer commute, prompting a greater possibility of initiating the relocation process to reduce commute time. The increased commute time will translate to an increase in their willingness to relocate. However, if the change in job is not sufficient enough to initiate the trigger, the household will not initiate the relocation process. The attributes used for relocation choice trigger (for  $i$ th household) include:

- $\Delta E_i$  : Change in job/income status for  $i$ th household from time  $t$  to  $t-1$ ,
- $\Delta HH_i$  : Household configuration change from time  $t$  to  $t-1$  and,
- $T_i$  : Tenure of  $j$ th household at time  $t$ .

The concept of household configuration change is represented as a function of the supply and demand number of bedrooms in the dwelling occupied by the household. The existing number of bedrooms represents the supply while the number of individuals in the household, and their household relationship determines demand. If the demand exceeds the supply, then the household will be more inclined to relocate, and vice versa. The formula is presented as follows:

$$\Delta HH_j = f(S_{bed}, D_{bed}) = S_{bed} - D_{bed} \quad (1)$$

where  $S_{bed}$  is the number of bedrooms in the current dwelling, and  $D_{bed}$  is the number of bedrooms required by household  $j$ . The number of bedrooms required by a household is a function of the number of adults (as couples) that are able to share a bedroom, and the number of children in the household (with provisions made for their age). Children over the age of 10 and relatives do not share a bedroom. Figure 2 illustrates the process of calculating a household's demand for bedrooms.



**Figure 2. Bedroom demand calculation.**

In situations where couples are married or de facto, or there are 2 or more children under 10, a room can be shared (to a maximum of 3 individuals per room). All other situations require that every individual in a household have a bedroom. Room stress or crowding in households has been the topic of little research in the academic literature. Typically, researchers have produced heuristic models that round out the number of bedrooms occupied by a household (or household level bedroom demand) by simplified means. One such example is the Equivalised Crowding Index method espoused by New Zealand residential planning authorities<sup>14</sup>, a linearized model of crowding in households used in population statistics of housing adequacy.

For the  $i$ th household at the HILDA data (for the Sydney metropolitan area), the probability of an active location choice trigger ‘ ’ within a year is modelled through a generalized linear model (GLM) as follows<sup>15</sup>:

$$\text{Pr}(Y_i = 1) = \frac{\exp(\eta_i)}{1 + \exp(\eta_i)} \quad (2)$$

where  $\eta_i$  is the linear predictor and is modelled by the inverse logistic link function:

$$\eta_i = \alpha + \beta_1 X_{i1} + \beta_2 X_{i2} + \dots + \beta_k X_{ik} \quad (3)$$

Here, the model intercept is denoted by  $\alpha$ , while  $\beta_1$  and  $\beta_2$  are the model coefficients. Using the HILDA available for 5774 households living at least for a year at the Sydney areas from 2001 to 2011, model coefficients are estimated using the Maximum Likelihood method. The results are presented in Table 1.

**Table 1. Model parameter estimates**

Model Covariates	Associated Coefficient	S.E.	Significance
Intercept	= 0.623	0.060247	<0.001
Change in income ( )	= -0.000125	3.81	
Household configuration change	= -0.06874	0.034107	0.043
Tenure	= -0.5766	0.014204	<0.001

#### IV. Discussion

Household relocation modelling is an integral part of the planning process as household locations determine demand for community facilities and services. The household relocation choice is important to assess the impact of migration among various metropolitan areas on the urban landscape. Thus, it is essential for planners to have a deep understanding of the impact changes in planning policy have on urban dynamics. Residential mobility is a process that has traditionally been modelled using aggregate forecasting that often provides a singular predicted state based on a certain statistical model and related assumptions. Given these conditions, this study developed a model that represents residential relocation choices autonomously at the household level.

Population modelling predicted a continuing trend of rapid urbanisation in 2007 and owing to the increasing population in Australia<sup>16</sup> with an estimated urban growth rate of 1.49% between 2010-2015. The Australian population is accustomed to high levels of wellbeing and quality of life and affords them the opportunity to live well. A valid evaluation of location-based human activities is required for urban designers and planners to make effective planning and appropriate decisions policy decisions that influence for maintaining and improving the quality of urban environments. It is critical for state and local governments, in developing and implementing long term land use master plans, to provide and maintain a series of benchmarks that measure the performance of urban environments and demonstrate a clear commitment to current and future residents. Such planning decisions require the capacity to assess and compare the impact of competing land use policies and infrastructure development. This research used a nominal Logit model to estimate the residential location choices of the population in Sydney Metropolitan Area. The main attributes of this model are change in household income, household configuration change, and the tenure of the household. HILDA data for 2001-2011 was used to estimate the coefficients in the Logit model. This model, validated against existing datasets, provides some indication that choice modelling is an appropriate means of modelling the autonomous nature of relocation choices made by households. How these choices affect the overall urban landscape is a product of a number of other interactions that are part of a larger research effort. However, the validity in the findings presented in this paper provide some guidance as to what predictive modelling tools can be integrated with other tools to provide the deeper understanding required for effective policy design.

In the analysis of data presented in Figure 1, it is expected that factors not captured in this study would undoubtedly cause movements in different parts of Australia. Using more accurate, and perhaps more sophisticated models, to further explore into the link between catastrophic events or government-driven redevelopment initiatives provides an exciting future research direction for this work.

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## Assessing The Impact Of Virtual Reality-Based Training On Health And Safety Issues In The Mining Industry

Shiva Pedram<sup>a\*</sup>  
Pascal Perez<sup>A</sup>  
Bruce Dowsett<sup>b</sup>

**Abstract:** Best practice in the mining industry includes extensive initial and professional training for staff involved in field operations. Whereas changes in mining technology and operations accelerate to improve productivity, health, and safety standards have to be continuously evaluated and improved, putting more pressure on training deliveries. Borrowing from Defence and Airspace industries, training in the mining industry is increasingly relying on immersive virtual reality to simulate complex operations and procedures in potentially dangerous environments. Coal Services Pty Ltd is at the forefront of modern training facilities in Australia. This paper presents a qualitative and quantitative research framework designed to analyse the impact of past and current training sessions on staff's ability to better perform their tasks, overall safety standards, and mine productivity. Interviews with trainees, trainers, and managers are used alongside session recordings to qualitatively evaluate levels of knowledge transfer and aptitudes to perform in a real environment. Then, a cost-benefit analysis is used to evaluate the added-value of virtual reality-based on technological and operational costs weighed against overall productivity of the mine being negatively affected by any safety issue.

**Key words:** Simulation; Modelling; Virtual Environment; Mining Industry; Safety; Highly reliable organisation.

### I. Introduction

A number of hazard industries have been trying to create the organisational and safety culture at their sites to transform the organisation into a highly reliable organisation. Highly reliable organisations (HRO) have been defined as organisations which are operating in hazardous condition but manage to almost sustain error-free performance; in such organisations the consequence of any error could be disastrous. There is abundant literature discussing the characteristics of HRO, key features that need to be adopted to create HRO or ways of controlling risks in hazards organisations but there is not much about methods of creating a HROs. We believe that Interactive virtual reality training environments can facilitate this transformation process for mining industry where it can change the hazardous organisation in to the HRO. There is an abundant literature on research dedicated to Interactive Virtual Reality (IVR) environments<sup>1-5</sup>, IVR-based teaching and training

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, NSW

<sup>b</sup> Coal Services Pty Ltd, Argenton, NSW

\*Corresponding author: Shiva Pedram [sp185@uowmail.edu.au](mailto:sp185@uowmail.edu.au)

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programmes<sup>6-8</sup> or their application to different industries<sup>9-14</sup> Literature investigating and evaluating the impact of IVR-based training programs on safety and productivity records is far less abundant. In order to evaluate the impact of IVR on creating HRO and substantially training delivery, improvement to safety records and overall impact on productivity, it is necessary to access and analyse data from past and current training programs, along with feedback from trainees, trainers, and various managerial levels. These data need to be processed within a formal analytical framework that can incorporate qualitative and quantitative data, microscale (training session) to macroscale (corporate) levels.

## II. Mine and Safety

There are two major thoughts that trying to explain accidents in complex, high hazard organisations: Normal Accident Theory (NAT) and High Reliability Organisation Theory (HROT). Normal accident theory was initiated by Charles Perrow<sup>15</sup> and its main focus was on the concept that accidents are unavoidable in complex organisations that operate in high-risk and technology situations. He believes that because of the two main characteristics of these sorts of organisations, tight coupling, and interactive complexity, failure occurs. On the other hand Leveson, et al.<sup>16</sup> argued that Perrow's categorising of industries in 'high risk' and 'low risk' category does not precisely reveal the accident rates and also theory offers a pessimistic view about accidents in complex systems and fails to suggest how the risk of accidents may be reduced<sup>17</sup> This criticism has been addressed by HRO which emphasise on understanding that under some conditions complex systems do not fail. HRO researchers argue that accidents in complex systems and hazardous organisations are not unavoidable because there are processes in place that allow high hazard organisations to efficiently prevent and avoid catastrophic errors helping them to attain a consistent record of safety over long time periods<sup>18-19</sup>

The mining industry faces both needs for high performance productivity and for drastic safety standards in the most hazardous working environments. Henceforth, it seems natural that the American Mine Safety and Health Administration (MSHA) asked the National Institute for Occupational Safety and Health (NIOSH) to explore and implement the use of IVR technology to develop training programs for open-cut or underground mining about hazard recognition, evacuation ways, and processes<sup>11</sup>. Likewise, South Africa started using IVR-based training programs in order to improve alarming workplace safety statistics. The South African Mine Health and Safety Authority (MHSA) started developing training environments as realistic and interactive as possible. Different technologies like joysticks, data gloves, or head-mounted displays were used to enhance trainee's immersion<sup>20</sup>. Open-cut or underground mining simulators provide safe, replicable, and cost-effective environments for miners to be trained and for engineers and managers to test different assumptions, strategies, and scenario outcomes. Henceforth, IVR-based training has the potential not only to improve workplace safety conditions, but also to contribute to a more effective management, more sustainable production, and, finally, more profitable industry<sup>13</sup>. In Australia, the NSW Mine Safety Advisory Council (MSAC) focuses on industry culture change through the implementation of mine safety plans and the improvement of technical and nontechnical skills at all levels of management. Lost-time injury, a usual metric used to assess progress, is defined as an incidence that causes a fatality, permanent disability, or injury resulting in time loss over one shift or more (Standards Australia, 1990). Table 1 presents the evolution of lost time injury in NSW over the last decade.

**Table 4. Lost time injury frequency rates in the NSW minerals industry (2000 - 2011)**

	Coal	Metalliferous	Extractive	All NSW mining
2000-2001	33.00	17.62	6.27	23.80
2001-2002	27.00	9.63	20.45	23.12
2002-2003	23.00	9.68	26.54	20.52
2003-2004	22.00	6.55	30.18	17.57
2004-2005	18.00	4.28	9.00	13.85
2005-2006	15.20	4.55	8.30	12.46
2006-2007	16.30	5.99	6.98	13.19
2007-2008	8.27	4.45	5.67	7.26
2008-2009	8.19	3.35	12.11	7.57
2009-2010	7.13	4.36	11.10	6.88
2010-2011	5.83	2.54	10.23	5.46

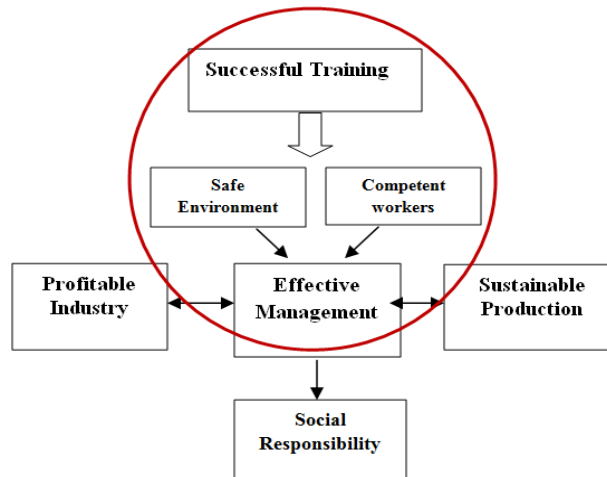
The main objective of this study is to analyse and evaluate the impact of IVR-based training on transforming the organisation into HRO through mining safety, management, and planning processes. In other words, we aim to evaluate the quality of the ‘training transfer’ which we believe play crucial role in developing HRO.

### III. Conceptual Framework

Wyk and Villiers<sup>21</sup> define IVR-based training environments as “real-time computer simulations of the real world, in which visual realism, object behaviour, and user interaction are essential elements”. The use of IVR-based training environments assumes that Human-Machine interaction stimulates learning processes through better experiencing and improved memorization, leading to a more effective transfer of the learning outcomes into workplace environments. As stated by Meadows<sup>22</sup>: “When I hear, I forget; when I see, I remember; when I do, I understand”. Fulton and colleagues<sup>23</sup> argue that interactive models like flight simulators are designed to improve trainee’s understanding of the consequences of decisional queues under limited resource availability (material, time, or energy) and uncertain or hazardous conditions (unintended consequences). The more realistic the experience is, the stronger the learning process. In situations where real life training opportunities are limited, hazardous or impossible, like emergency responses, virtual reality simulators offer the opportunity to emulate many wide-ranging experiments<sup>24</sup>.

A crucial condition for IVR technology to deliver satisfying training transfer is its ability to reproduce faithfully not only the physical environment but also functional features of the simulated operations. In the case of flight simulators, Hays and colleagues<sup>25</sup> demonstrated that the quality of training transfer is highly correlated to the level of fidelity of the simulated environment to the real world. Orlansky and String<sup>9</sup> argue that the effectiveness of IVR-based training is influenced by (1) the type of simulator in use, (2) the level of experience of participants, and (3) the quality of scenario design and delivery.

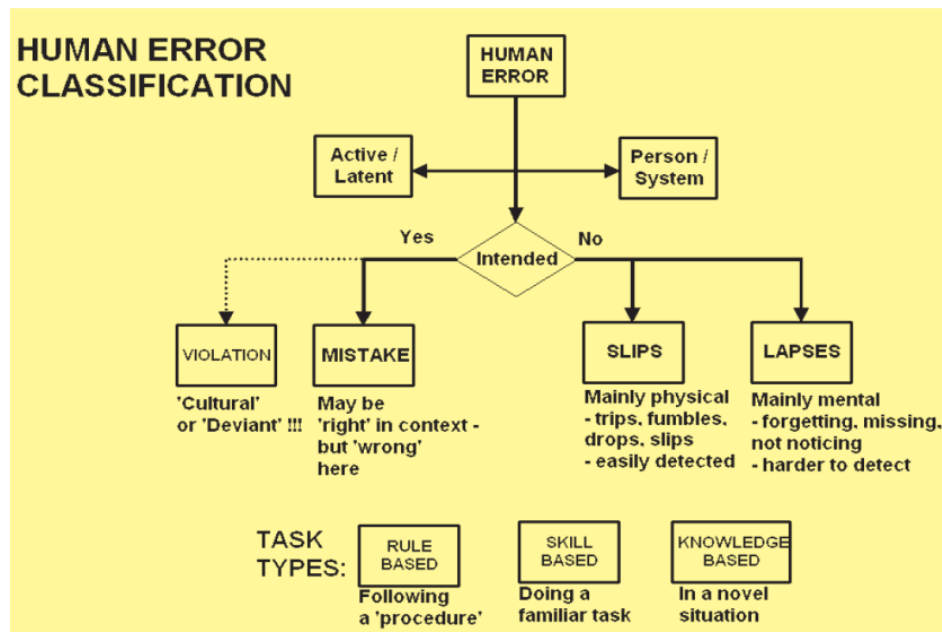
A successful mining training program, being IVR-based or not, should result in the creation of a safer workplace (‘the mine’) and a more competent workforce (‘the miners’), contributing to a more effective management of field operations. In turn, improved management will have significant and durable impact upon higher industry objectives like sustainable production, corporate profitability, and social responsibility (Figure 1).



**Figure 1. Potential impact of IVR-based training on various aspects of mining operations**

#### A. A more competent workforce

Most of the time, incidents result from human errors or uncontrolled situations. In a workplace context, a human error is defined as an action, intentional or not, having a negative impact on safety or productivity. This definition covers a large range of circumstances like tripping over, slipping, bending a rule, violating a procedure, or having a lapse of concentration (Figure 2).



**Figure 2. Human Error Classification (source: TIRE, 2013)**

The assumption behind the development of IVR-based training for the mining industry is that it will produce more aware and better prepared workers, at a competitive cost, compared with more traditional approaches. In a context where real world training is whether too dangerous or too demanding on production, investing in virtual reality technology seems to be a reasonable choice<sup>26</sup>. Drawing from the flight simulator paradigm<sup>9</sup>, mining simulators are designed to accelerate a worker's learning curve in a realistic but safe environment through

repeated experiments. Causal queues and repetitions are meant to stimulate individual experiences and to enrich corresponding mental models. Ultimately, this learning in context should limit the number of human errors to a tolerable level as skill sets dramatically improve<sup>12</sup>.

#### **B. A safer workplace**

Salzman and colleagues<sup>6</sup> argue that IVR-based training can support a second-order learning process through which designers, trainers, and managers gain insight into interactions between workers and their environment. Analysing training scenarios, trainee's performance and feedback after the session could lead to better workplace conditions by modifying features of the current environment. Henceforth, mining simulators could become platforms for testing and implementing new ideas developed by engineers or managers with immediate (and safe) response from the workforce. To our knowledge, the use of IVR-based simulations to improve the working environment has not received enough attention yet.

### **IV. Research Method**

Our case study focuses on a training facility located in Wonoona (NSW) operated by Coal Services Pty Ltd, an Australian service provider. The objective is to evaluate the impact of IVR-based training programs on worker's competences, safety records, and mine productivity. Interviews with trainees, trainers, and managers alongside direct recording of training sessions will constitute our primary data. Secondary data will include records of previous sessions and industry assessment documents. Qualitative and quantitative analyses will be performed to evaluate the level of knowledge transfer and aptitudes to perform in a real environment. Then, a cost-benefit analysis will be used to evaluate the added-value of virtual reality-based on technological and operational costs weighed against overall productivity of the mine being negatively affected by any safety issue.

#### **A. Qualitative Analysis**

Assessing the quality of a training transfer involves three components: 1) Inputs including trainees 2) Outputs including learning and performance, and 3) Training conditions including the environment. According to Salzman et al.<sup>6</sup>, there is a strong relationship between IVR features, individual characteristics, and the IVR-based learning experience. In order to estimate the strength of this relationship across various groups of trainees and training scenarios, we will gather evidence at different stages:

##### **1) Before Training**

The focus will be on trainees' characteristics and their competency and knowledge level prior attending the training sessions. The tools to collect these primary data will include individual questionnaires, interviews with managers and performance sheets. Whenever applicable, we will also ask trainees to draw causal loops diagrams of hypothetical scenarios before attending the session.

##### **2) During Training**

Aside from the electronic recording of training sessions by the Facility, we will conduct direct observations of individual and collective response to stimuli at specific stop points. These observations will include body language, oral communication between trainees or collective organisation during an exercise. The aim is to evaluate the learning experience.

### 3) After Training

At the end of a session, individual questionnaires and interviews will be used to record feedback from trainees and trainers. This material will be used to analyse individual responses to an IVR environment and to evaluate the quality of the training transfer in terms of competency. We will also attend debriefing sessions between trainees and trainers. Whenever applicable trainees will be asked to create a second causal loop of hypothetical scenarios in order to compare them with the initial ones.

### B. Quantitative Analysis (Cost-Benefit Analysis)

Based on Yamnill and McLean<sup>27</sup>, training is pointless if it cannot be expressed through a performance measurement. Training should focus on performance and not only on learning. Whenever training can demonstrate a subsequent gain in performance then the training transfer is positive. Conversely in the absence of any gain in performance, the training transfer is negative<sup>27</sup>. Wehrmann et al.<sup>28</sup> argue that a key point to assess the benefits of a training program is to evaluate its impact directly onto workplace performance. In this case, we propose to adapt the approach proposed by Micheli<sup>29</sup> to measure the quality of training transfer for flight simulators. This approach includes two indicators: (1) the Performance Enhancement Measurement (PEM) and (2) the Effectiveness for Training Purposes (EfTP).

### C. Performance Enhancement Measurement

PEM represents the amount of time saved to finish a task due to the IVR-based training sessions. It can also represent the enhancement in performance of employees after attending the training sessions. In this equation:

$Y_c$ : Indicates the number of hours required by the employee to finish a certain task without attending the training sessions in IVR environment.

$Y_x$ : indicates the number of hours required by the employee to finish the same task after attending the training sessions in IVR environments.

$$\text{Percent Saving} = \frac{Y_c - Y_x}{Y_c} \times 100 \quad (1)$$

The greater the number the higher is the savings. Values for  $Y_c$  and  $Y_x$  will be derived from interviews with trainees and different levels of management.

### D. Effectiveness for Training Purposes

TE ratio indicates the amount of time saved compared to the amount of time spent in the simulator:

$$\text{Transfer effectiveness ratio} = \frac{\text{Number of training unit in simulator}}{\text{Number of unit in the Mine for equivalent training}} \quad (2)$$

The greater the number the better is the training transfer. If trainee received 50 hours of training in IVR environment and in return he/she can finish the task in 30 hours (Transfer effectiveness ratio – TER= 1.6) compare to the time before attending the training session in IVR environment and receiving different trainings for instance if it took him/her 40 hours (TER= 1.2) then the transfer effectiveness of IVR environment is 1.6 compare to 1.4. Figures associated with number of hours to perform a task will be derived from interviews with trainees and different levels of management.

Using PEM and EfTP indicators to assess potential benefits, we will use a costing model to conduct our cost-benefit analysis. For example, Rai and Wong<sup>30</sup> suggest that a flight

simulator costs only 15% of using actual helicopters for training purposes. Drawing from their study, we have selected the following cost categories:

- Costs associated with designing and developing a simulator.
- Costs associated with operating an IVR-based training session.
- Specific technology costs (Curve screen, Domes, 360 degree theatre).

## V. Conclusion

This paper presented the research framework to quantitatively and qualitatively evaluate the effect of IVR-based training on training transfer in the mining industry. Two main components of effective management have been identified as a competent workforce and a safe workplace. Our evaluation framework will be applied to an IVR-based training facility operated by Coal Services Pty Ltd in Woonoon (NSW, Australia). Our methodology aims to collect a broad range of performance, behavioural, and attitudinal data to help with a qualitative and quantitative analysis of the impact of mining simulators on improving workforce's performance and workplace's safety records. These data, associated with cost estimates, will provide a reasonable basis for conducting a cost-benefit analysis that will provide the industry with an evidence-based outcome to examine its future investments in this technology.

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# Evaluation of Accessibility Measures in Practitioner Policy and Their Effectiveness in Non-Metropolitan Areas

Brett Williams<sup>a\*</sup>

Pascal Perez<sup>b</sup>

**Abstract:** Various accessibility measures exist to explore the performance of transport by quantifying the opportunities available at a particular, discrete location and the available means to travel both to and from these opportunities. In Australia there is currently no consistent performance measure used by regulatory authorities to evaluate accessibility in order to inform land-use planning decisions. Considering the widespread availability and usage of strategic transport modelling software, a unified accessibility metric would benefit practitioners when planning for future infrastructure needs. Furthermore, the development of accessibility measures has tended to focus on metropolitan areas without widespread exploration of their effectiveness in regional and rural areas, where public transport, walking and cycling opportunities are limited due to lower population densities and wider disaggregation of localities. This paper provides a review of the existing literature on accessibility performance measures, and identifies areas of potential research on transport accessibility in non-metropolitan areas, with the aim to improve the planning and delivery of future infrastructure needs in an optimised and sustainable manner.

**Key words:** Accessibility; Land use planning; Local government; Non-metropolitan areas; Policy; Transport

## I. Introduction

Many local government authorities have received criticism for a lack of strategic vision towards urban development and inadequate provision of transport infrastructure. While geographic and historical legacies often hinder genuine attempts to develop such a strategic vision, evidence suggests that traffic congestion, ineffective and under-utilised public transport, and inadequate road infrastructure stem from inefficient connectivity between land use and transport systems. This paper discusses a proposal to evaluate connectivity through a single indicator: the level of accessibility.

Austrroads<sup>1</sup> defines accessibility as ‘the variety of opportunities provided to people through efficient arrangement of land use and various modes of transport’. Accessibility can be used to compare one particular location to another in terms of the opportunities available and means to travel to and from these opportunities. This information can in turn be used to analyse how effective an area is in terms of how it connects to its surrounding area, or how accessible it is. Accordingly planning authorities can target areas of good accessibility by

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<sup>a</sup> Shoalhaven City Council, Nowra NSW 2541, Australia

<sup>b</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong, NSW 2522, Australia

\*Corresponding author: Brett Williams [williamsb@shoalhaven.nsw.gov.au](mailto:williamsb@shoalhaven.nsw.gov.au)  
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intensifying land use, or conversely target areas of poor accessibility by seeking to improve the transport network.

In Australian local government transport practitioners rely upon various standards and guidelines developed by state and national regulatory bodies to develop best practice in transport management, and by adopting certain unified performance objectives this allows practitioners to work towards consistent outcomes across different jurisdictions. However the benefits of considering accessibility, which combines both land use planning and the transport system that serves it, are not effectively exploited in the standards, policies and guidelines that are currently available.

Critical analysis of the existing literature suggests that accessibility can be a powerful measure to inform practitioners when making decisions on land use planning if developed effectively. Considering the current widespread availability and use of transport modelling software, practitioners and in turn the broad community would benefit from a unified accessibility performance measure that applies not only to metropolitan areas, but also to regional and rural areas. The literature reviewed in this paper confirms the lack of integration between theory and practice, especially in non-metropolitan areas, as well as identifies existing accessibility measures that can be analysed further, to investigate the utilisation of accessibility as an effective and transferable measure for practitioner utilisation with a focus on non-metropolitan areas.

## **II. Defining Accessibility**

Accessibility in the context of transport analysis is defined in abundance throughout the relevant literature which dates back over half a century. Whilst its definition is generally consistent, care should be taken to clearly identify its function when discussed. One example describes accessibility as being ‘determined by the spatial distribution of potential destinations, the ease of reaching each destination, and the magnitude, quality, and character of the activities found there’<sup>2</sup>.

Focussing on passenger transport, accessibility is defined as the extent to which land use and transport systems enable individuals, or groups of individuals, to reach destinations by means of a combination of transport modes<sup>3</sup>. Delving into the concept of social participation, accessibility is considered to be vital to the liveability of an area, and its economic, social and environmental well being, whilst also concerning the ability of an individual to obtain goods and services, participate in the workforce, interact in the community and undertake recreational pursuits<sup>4</sup>. Paez, Scott and Morency<sup>5</sup> also offer a brief definition of accessibility as ‘the potential for reaching spatially distributed opportunities (for employment, recreation, social interaction, etc.)’, however expand this concept by categorising accessibility as being either normative (prescriptive), or positive (descriptive) when considering measures used to address substantive planning and policy questions. The distinction being made is that normative accessibility considers ‘how far people ought to travel or how far it is reasonable for people to travel’, whereas positive accessibility considers ‘how far people actually travel’. The significance of this dichotomy, which has not been clearly defined in previous literature, is that accessibility should also consider the actual experiences of individuals (and possibly their perceptions), as opposed to only being based on assumptions of what is deemed reasonable.

In Australia recent developments on accessibility have been led by Austroads and the Australian Road Research Board (ARRB), who have combined to produce a research report with the purpose of developing an accessibility assessment framework for policy analysis and performance monitoring<sup>1</sup>. This report states that accessibility ‘measures the ease with which people are able to find and reach the best suited opportunity, either for work, study and others’, and covers the transport modes of car, public transport, walking and cycling. In a separate paper authored by the ARRB staff who contributed to the above Austroads Research Report, they define accessibility as combining ‘land use and transport together like two sides of a coin’<sup>6</sup>.

Another perspective on accessibility is that people value both destination convenience and choice, and that the value placed by people on the ability to access a particular destination is unique for different people and destination types<sup>7</sup>. The examples provided above demonstrate that ample literature regarding the concept of accessibility is available. However, some alternative definitions should also be considered to best understand accessibility. In an earlier Austroads publication it is reported that accessibility ‘is always understood to be the ease of getting to something, and the various uses of the term differ in the types of things that can be reached’, however confusion has arisen when considering ‘access’ as opposed to accessibility<sup>8</sup>. Generally access refers to physical mobility, such as people with disabilities in the context of design (such as the provision of ramps and dedicated parking spaces), and care should be taken to clarify the context of the subject matter when the term accessibility is being used to eliminate any potential ambiguity. An example of this reinforcement is provided by Geurs and van Wee<sup>3</sup>, who qualify their paper by stating ‘[h]ere, access is used when talking about a person’s perspective, accessibility when using a location’s perspective’. Conversely, an alternative way to study accessibility is to consider its reciprocal, which is defined as ‘remoteness’ when analysing regional and rural areas<sup>9</sup>.

### **III. Integration of Theory and Policy**

A common theme encountered in literature is the lack of effective integration between accessibility in theory and its use in transportation and land use planning practice. Handy and Niemeier<sup>2</sup> state that whilst the concept of accessibility is used in the language of planners, it has rarely been transformed into performance measures for the evaluation of policies and has had little practical impact. Similarly in another study that explores the use of quality of life as an accessibility indicator, when used by governments and local partnerships it was found that these indicators tend to be developed in accordance with policy or politically-motivated targets, with minimal consideration of individuals’ perception and the eventual outcomes<sup>10</sup>.

Furthermore Paez et al.<sup>5</sup> report that effective use of accessibility in planning ‘has been hampered in the past by limited understanding of the measures, definitional issues, and measurement problems’, and have ‘led to the use in practice of simple but partial performance measures’. Their consideration of normative versus positive accessibility measures is significant, as this addresses the deficiencies of policy when it is based purely on assumptions or antiquated conventions reproduced from existing literature – the danger here being the automatic assumption of legitimacy when a fact is presented in peer-reviewed literature. This reinforces the need to consider the positive aspects of accessibility sourced from the real activities performed by individuals when using transport, and even their perceptions of how they use it.

There are however some examples of accessibility measures being used effectively. In one case a tool available through the website of Sutherland Shire Council<sup>11</sup> offers a mapped Accessibility Index based on walking and public transport opportunities for each parcel of land in the Council's local government area. This Accessibility Index was developed following the Council's desire to address accessibility issues and included data obtained from a telephone survey of residents to ensure that the index reflected the community's opinion<sup>4</sup>. Whilst clearly a useful tool for residents and visitors to the Sutherland Shire, in its current form it would have limited benefit in regional and rural areas where there is often a lack of public transport, walking and cycling opportunities due to dispersed urban development.

Another example of effective use of accessibility as a measure involved a coalition of organisations called the Sydney Alliance who commissioned the development of maps to explore inequality on Sydney's public transport network, which was reported on ABC News Online<sup>12</sup>. This study demonstrated that whilst a considerable proportion of the population lived in close proximity to public transport opportunities, only a small number of locations had services available every 15 minutes or less, thus emphasising a potential aspect of the transport network that could be improved.

Austrroads provides some guidance on how the development of accessibility based network performance measures can help assess networks in terms of specific policies<sup>8</sup>. However this report is based on the evaluation of the whole of Australia and is unlikely to be suitable for detailed analysis of smaller study areas, and may be considered to be out of date given the increased performance of computing power available in the intervening years. The Austrroads research report on the Application of Accessibility Measures however offers strong potential to provide a unified accessibility measure, named the ARRB Accessibility Metric (AAM), for Australian practitioners, based on four land use 'opportunities', and four travel modes as shown in Table 1.

**Table 1. ARRB Accessibility Metric Inputs- reproduced from the Austrroads research report on the Application of Accessibility Measures (2011)**

<b>Opportunities</b>	<b>Travel Modes</b>
Jobs for employment	Car
Enrolment for school	Public Transport
Workers in the retail industry	Walk
Workers in the recreation industry	Cycle

The Austrroads report compares the AAM against two other accessibility measures, however it is notable that both of the case-studies used to test these measures were state capital cities Melbourne and Perth, and no detail was provided on the potential to utilise this measure in non-metropolitan areas where public transport, walking and cycling options can be limited.

#### **IV. Accessibility Measures in Non-Metropolitan Areas**

As is the case with most theoretical literature and policy from higher-order authorities, the focus tends to be on the major metropolitan areas, due to the general perception that the problems are a greater issue where population densities and infrastructure utilisation is higher. Handy and Niemeier<sup>2</sup> provide a comprehensive review on the history of accessibility measures, however the authors appear to consider accessibility as an issue affecting only metropolitan areas. Furthermore, a key attribute of the Accessibility Constraints Map

developed for Sutherland Shire Council is its ability to be transferable to other Councils, although as previously raised this would have limited benefit in non-metropolitan areas<sup>4</sup>.

In the Austroads Guide to Transport Planning, it is reported that ‘there are few planning guidelines that have been separated for urban and rural areas at the national, state/territory and local government level’, and that the most obvious differences when comparing urban and rural communities ‘are those related to access and affordability’<sup>13</sup>. Whilst also stating that transportation planning needs to consider the many barriers to access that currently exist for rural communities, and the difference in the characteristics of these barriers when compared to urban dwellers, it is noted that other issues need to be considered across the whole transport network (whether urban or rural) such as the long-term strategic consequences of planning actions taken on liveability of locations. Furthermore, the Austroads report on rural accessibility provides an example of applying a basic accessibility measure across the whole of Australia from a broad strategic perspective<sup>8</sup>.

A separate analysis studying rural Australia discusses the perception that there are few problems regarding mobility and accessibility in remote areas, mainly due to a lack of research on the indication of people’s ability to overcome the vast distances involved<sup>14</sup>. This paper defined rural areas as those with settlements having a population less than 5,000, which was based on the lowest level of ‘service centre’ defined in the Accessibility/Remoteness Index of Australia (ARIA) scores developed by the Federal Department of Health and Ageing.

Another study involving remote communities performed vulnerability analysis of regional road networks, and suggested use of accessibility indices as metrics for vulnerability<sup>9</sup>. This study also utilised ARIA scores to develop a measure to undertake assessment of the impacts of network degradation, stating that ‘there is an important place for regional studies and for planning tools able to assist in analysing the social-economic consequences of network performance on rural populations’.

## V. Conclusion

The preliminary literature review provided in this paper introduces accessibility as a concept that describes the opportunities available at a particular, discrete location and the available means to travel both to and from these opportunities. Care must be taken to clearly define the use of the term accessibility due to the potential for ambiguity.

It is evident that further work is required to better integrate theoretical transport accessibility into policy for practitioners to investigate the combination of transport and land use, and how they are effectively utilised by a population that displays wide spatial and demographic characteristics. It is clear that there is as a lack of detailed studies into non-metropolitan areas. There is also the potential for a unified accessibility measure to be developed that allows accessibility to be used consistently across jurisdictions, and effectively inform and improve land use planning decisions in practice. Upon development, this measure is proposed to be investigated as part of a practitioner-based Masters by Research project using the Shoalhaven local government area as a case study, and eventually incorporating these results into the SMART Infrastructure Dashboard<sup>15</sup>.

The outcome of this research project has the potential to contribute towards the theory of accessibility, especially in non-metropolitan areas, and how it can be better integrated with

practice. Subsequently, the development of an effective accessibility measure also has the ability to be utilised by engineering and planning practitioners, leading towards more efficient utilisation of urban lands and improved transport outcomes. In the face of issues such as climate change, continual population growth and the increasing cost of infrastructure, this project has the ability to contribute towards addressing these challenges.

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# **The roles of evolutionary computation, fitness landscape, constructive methods and local searches in the development of adaptive systems for infrastructure planning**

Mehrdad Amirghasemi<sup>a\*</sup>  
Reza Zamani<sup>a</sup>

**Abstract:** Modelling and systems simulation for improving city planning, and traffic equilibrium are involved with the development of adaptive systems that can learn and respond to the environment intelligently. By employing sophisticated techniques which highly support infrastructure planning and design, evolutionary computation can play a key role in the development of such systems. The key to presenting solution strategies for these systems is fitness landscape which makes some problems hard and some problems easy to tackle. Moreover, constructive methods and local searches can assist evolutionary searches to improve their performance. In this paper, in the context of infrastructure, in general, and city planning, and traffic equilibrium, in particular, the integration of these four concepts is briefly discussed.

**Key words:** Evolutionary computation; Local search; Infrastructure; City planning; Traffic equilibrium.

## **I. Introduction**

Infrastructure is a term used to indicate both organizational and physical structures a society or an enterprise needs to function. In effect, all facilities and services needed for the operation of an economy is gathered under the umbrella term of “Infrastructure”. Each Infrastructure includes connected elements which are structurally related and each element can affect the other elements. It is through this interconnection that these elements collectively provide a basis for structural development of a society or an enterprise.

Viewed in an operative level, infrastructure makes the production of goods and services required in the society more straightforward and the distribution of finished products to market easier. Whereas these services comprise a wide range from health-care through transportation to education, the produced goods encompass a range from agricultural products through furniture to electronic appliances.

A better supply of accommodation, water, food, telecommunication, electricity, transportation, and waste disposal, as seven major requirements of a society, all depends on

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<sup>a</sup> SISAT, Faculty of Engineering and Information Sciences, University of Wollongong, NSW 2522, Australia

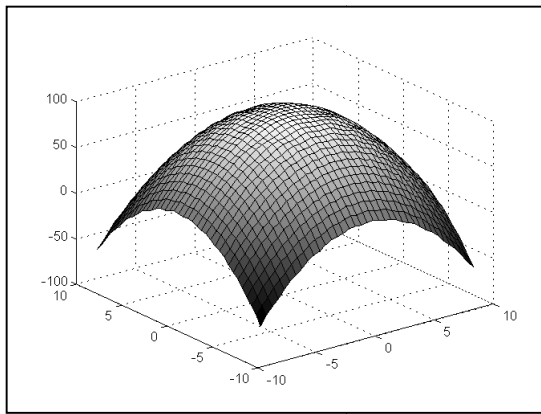
<sup>\*</sup>Corresponding author: Mehrdad Amirghasemi [mehrdad@uow.edu.au](mailto:mehrdad@uow.edu.au)  
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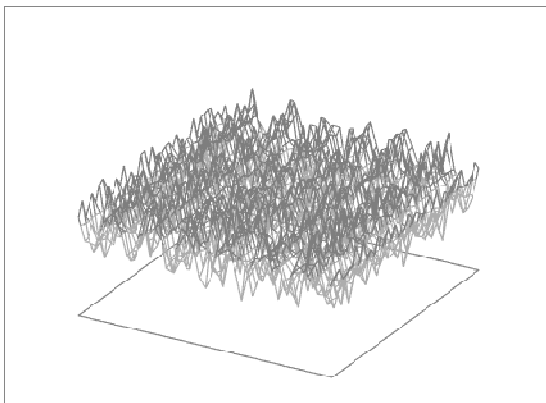
the sophistication of the corresponding infrastructure. Any of these seven major components is either related to providing services, producing goods, or distributing finished products to the points of demand.

Because of the complication of these systems, reaching a reasonable level of efficiency and effectiveness is highly related to employing sophisticated optimization techniques and mathematical programming. This is involved with the optimized selection of a set of values for a number of variables among a set of available alternatives determined by the existing constraints towards minimizing or maximizing a given criterion.

Figures 1 and 2 show a simple and a hard optimization problem, respectively. Because of the complicatedness mentioned, most of the optimization problems in the area of infrastructure belong to the second category. Moreover, each optimization problem can be located in a 3-dimensional space with the three axes of time-horizon, number of variables, and probabilistic nature (0-1).



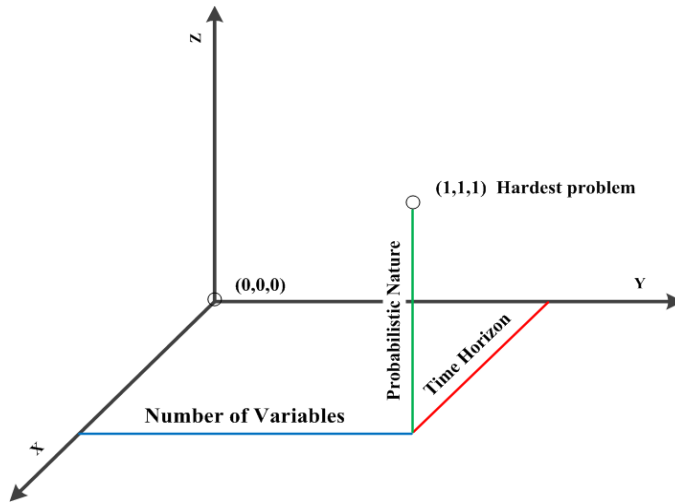
**Figure 1.** The fitness landscape of an easy optimisation problem.



**Figure 2.** The fitness landscape of a hard optimisation problem.

Figure 3 shows such a space and that the larger the distance of a problem form the origin (0,0,0), the harder the problem can be. In the area of infrastructure, the number of variables is high, the time-horizon is large, and the probabilistic nature is at the extreme, indicating the tremendous hardness of such problems in comparison of other problems. For instance, the

time horizon of such problems is between five to ten years, and these problems are involved with enormous number of variables, which have mainly stochastic nature. Because of such extreme hardness, modelling and simulation of infrastructure problems are complicated issues and are involved with the development of highly effective systems that can learn and respond to the environment intelligently.



**Figure 3. A 3-Dimensional representation of problem difficulty.**

With traditional optimization techniques being ineffective or infeasible for such problems, simple agents with limited intelligence can collectively represent complex behaviour and assist infrastructure planning. As a subfield of computational intelligence, and inspired by the biological mechanisms used in nature, genetic algorithms are based on an iterative process which controls the growth and development of a population of solutions competing to survive. The key point with genetic algorithms is the ease of their implementation on massively parallel processors, which makes their solution remarkably easier to obtain.

Using sophisticated techniques and relying on the survival of the fittest solutions, evolutionary computation can highly support infrastructure planning and play a key role in the development of such systems. Despite the fact that genetic algorithm is only one of the three branches of evolutionary computation, and genetic programming and evolution strategies are the two other branches,<sup>1</sup> in the rest of the paper we use the term genetic algorithms and ignore the other two branches for simplicity.

Despite their robustness, genetic algorithms do not have any fine tuning capability and can be integrated with local searches to remove this shortcoming. Since both local searches and evolutionary searches require initial solutions to start, these integrated systems also require an effective constructive method as well. The key to presenting solution strategies for these integrated systems is fitness landscape which makes some problems hard and some problems easy to tackle. The rest of the paper is as follows. Section II briefly discusses the outlines of two infrastructure models with their corresponding references. Section III explains hybrid strategies which include evolutionary search techniques, constructive methods and local searches and also discusses the concept of fitness landscape. Section IV provides concluding remarks and discusses the advantages and disadvantages of evolutionary search techniques for infrastructure problems.

## **II. Two examples of highly sophisticated infrastructure models**

In this section, two related infrastructure models are presented and their complexities are discussed. The first model is related to a high-way construction problem and the second model discusses the proper allocation of available regions to residential, commercial, industrial and educational complexes. Examples of educational complexes are universities and TAFE, and examples of commercial complexes are shopping centres and malls. We first start with the highway construction and then continue with the problem of proper allocation of available regions to the complexes.

### **F. Traffic equilibrium and highway construction**

City Transportation is the movement of people from one location of the city to another. The main modes of transport are roads, streets, highways and railways. In a city, transportation infrastructure is as important as a telecommunication infrastructure, because it enables personal communication among people, which in turn facilitates daily work. Decisions about the improvement of transportation infrastructure, however, are among the most complex decisions. Part of this complexity is because of the extreme interplay of variables with one another. For instance, establishing a highway between the two points of “a” and “b” affects the load of traffic in points much further than these two points. Exactly the same as a succession of processes such as the components of the electrical circuits and chemical reactions, in which each element activates other elements, all elements of transportation affect the other elements to a considerable extent.

This succession of processes makes the construction of new highways as one of the most expensive activities in improving an urban infrastructure. When a budget is assigned to highway construction projects, the main question is that to which highways this budget should be assigned. The answer to this question depends on how different ways of spending this budget changes the traffic flow. Traffic flow itself is the study of interactions among drivers to select their path to reach their destination from the origin they have started in the shortest possible time. The decision of drivers not only depends on the decision of other drivers but also on the available streets, roads and highways. Depending on some particular spending of such a budget, some drivers may also switch from using their private car to public transportation.

The study of this complicated system and the way passengers, in general, and drivers, in particular, connect their origin to their destination highly affects the development of an optimal road network. In effect, without sophisticated optimization techniques in assigning budgets to the development of highways, efficient movement of traffic is near to impossible. Figure 4 shows a simplified model for spending a certain budget for developing a number of possible highways. Interested reader may refer to the related studies in road network design for more info.<sup>2</sup>

1. Find the interplay among variables through Origin / Destination data of traffic;
2. Considering the problem constraints, test possible scenarios for highway construction through calculating average time spent in traffic and cost;
3. Select the best alternatives with respect to the total budget;
4. Decide about the highways to be constructed based on the allocated budget.

**Figure 4. A simplified model for spending a certain budget for developing a number of possible highways**

### **G. City planning through allocation of regions to complexes**

City planning is a technical process corresponding to the design of the urban environment to ensure an orderly development of settlement. Extremely concerned with analytical issues and systems planning, it can take a variety of forms and its output is involved with the systematic recommendation about the installation of different complexes, from libraries through shopping centres to recreational centres, in different locations of the cities. The possible construction of a site, depending on whether it is residential or non-residential, causes the production or attraction of many different trips. Non-residential complexes can be educational, commercial, industrial, recreational, or medical, with each of these types of complexes absorbing particular trips.

Assume that there are  $n$  sites and  $m$  complexes to be built. The strategic infrastructure question is which site should be allocated to each complex. In effect, such a question is concerned with a very large search space and is involved with highly sophisticated modelling and computer programming. A mathematical model for allocating proper sites to possible complexes is highly multifaceted. Figure 5 shows a simplified model for the allocation of regions to complexes. Interested reader may refer to related studies.<sup>3</sup>

- 1 Find the interplay among variables through Origin / Destination data of traffic;
2. Considering the problem constraints, test possible scenarios for assigning; regions to complexes through calculating average time spent in traffic and cost;

**Figure 5. A simplified model for the allocation of regions to complexes**

As is seen, there are several key points in the commonality and differences of the two aforementioned models. First, both models use the current Origin / Destination data and extend it to the future, when the construction of the project is completed, whether it is the construction of the highways or the complexes. Second, both models have the same objective function of minimizing average time spent in traffic. Third, in the first model, the decision variables comprise a vector of size  $n$ , in which  $n$  shows the number of highways that can be

constructed whereas in the second model, the decision variables establish an  $m \times n$  matrix, where  $m$  and  $n$  show the number of available locations and complexes, respectively.

### **III. Evolutionary search techniques, constructive methods, local searches and fitness landscape**

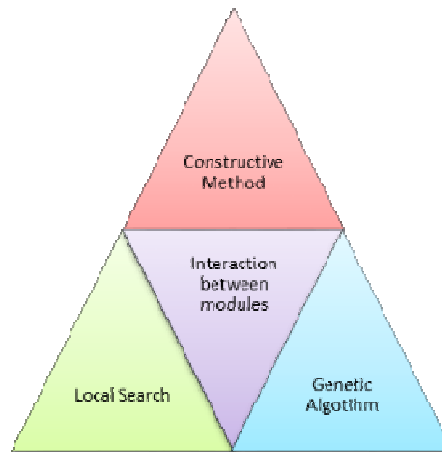
In solving the problem of city planning through allocation of regions to complexes, a building block is as follows. Given a set of  $n$  facilities and  $n$  locations, and two  $n \times n$  matrices, one representing the flow between each two facilities,  $f_{ij}$ , and the other representing the distance between each two locations  $d_{kl}$ , the goal is to find an arrangement  $\pi$  for the facilities that minimizes the volume of traffic among the facilities. This is an old and notorious problem in optimization called facility-layout problem. In the optimization literature, some researchers have also called it Quadratic Assignment Problem.<sup>4</sup> Based on this notorious problem, the traffic volume is the sum of all possible distance-flow products.

For this problem, the most effective meta-heuristic procedure can be classified under three main categories of constructive methods, local searches and genetic algorithms. In constructive methods, a solution is constructed step-by-step. In fact, solution elements are determined at each iteration based on a heuristic procedure. On the other hand in local searches a complete solution is improved by iteratively applying certain operators such as swapping the location of two facilities. In the third category, genetic algorithms, a population of solutions are collectively evolved via competition and cooperation of individual solutions through selection and recombination operators, respectively.<sup>5</sup>

The evolutionary search procedures for tackling this problem adaptively employ the three mentioned search paradigms and can be illustrated by Figure 6. In fact, first, a constructive procedure is used to build an initial pool of high quality solutions. Next, an enhancement procedure is applied to all individual solutions in the pool for further improvement. Finally, the genetic algorithm tries to produce higher quality solutions (offspring) by combining the current enhanced solutions (parents). The success of these hybrid procedures in tackling combinatorial optimization problems is the main motivation in using adaptive, hybrid meta-heuristics for complicated infrastructure problems.

Based on “No-free-lunch” theorem grounds,<sup>6</sup> incorporating problem-specific knowledge, and matching the “procedure” with the “problem” is essential to develop high performance problem solvers. Nevertheless, the ideal case is to have a procedure as generic as possible to solve a class of similar problems effectively. To balance this dilemma, we require the proposed model to be as modularized as possible, separating the problem-specific parts from the generic parts.

The other concern in the development of efficient meta-heuristic procedures is the notion of fitness-distance correlation in the search landscape. For instance, using solutions obtained from a constructive procedure as initial solutions as an input solution for other modules, significantly increases the quality of the final output solution. This improvement in solution quality is amplified when the fitness-distance correlation is high and the problem search landscape has a “big valley” structure.<sup>7-8</sup>



**Figure 6. The modularisation of the hybrid models for infrastructure problems**

#### **IV. Concluding remarks**

Modelling and simulation of infrastructure problems are complicated issues and require a sophisticated solution methodology and scientific analysis. That is why without scientific analysis of a city and its surroundings and without having an intricate solution methodology, the planning of the extension of the city leads to serious issues. A laborious project concerned with the scientific analysis of the city requires many technical details and the result can be represented as a model. These models are highly complicated and because of their involvement with a wide variety of interacting variables, cannot be solved easily. Physical processes on which the history of life is explained can be imitated to tackle these hard-to-solve problems.

The main notions of such a solution methodology are mutation, reproduction, and most importantly the survival of the fittest. For several reasons, genetic algorithms are of key importance in solving the models presented in this paper. First, as a population-based approach, genetic algorithms are intrinsically parallel and this facilitates the solution of many hard-to-solve infrastructure problems. Second, they are highly adaptive and flexible and this contributes to their wide applicability. Third, they can operate in large search-spaces effectively, and fourth, they are easy to implement. An evolutionary search technique maintains a population of solutions, impose random changes to these solutions mainly through mutation and crossover operations and applies the survival of the fittest principal to the pool of solutions, with a selection process directing which solutions can participate in crossover operations and which survives for the next pool.

Without using construction methods and local searches, the application of genetic algorithms, however, cannot produce high quality results. Hence the integration of construction methods, local searches and genetic algorithms seems to be an effective approach in dealing with these highly complicated problems. Fitness landscape of these problems can determine how this integration can best be performed.

In both of the presented models, the origin-destination data were used. Origin-destination surveys can be simply performed in different cities to determine the transportation needs. The

typical outputs of these systems are several matrices, with each matrix related to a different purpose of traffic in different hours of the day for different modes of transportation. Each cell (i,j) of such matrices shows the number of trips from origin i to destination j. In other words, before such a study, the city should be divided into a number of zones. For instance, if the city is divided into 500 zones, then all these matrices are of the size 500×500, which is computationally demanding. The understanding of the underlying characteristics of travel is, however, only possible through the study and manipulation of these matrices.

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# Governing Complex Infrastructure Developments: Learning From Successful Megaprojects

Tim Brady<sup>a</sup>  
Andrew Davies<sup>b</sup>

**Abstract:** Past literature suggests increasing complexity in projects may be a significant factor in project failure (e.g. Morris & Hough<sup>1</sup>, Miller & Lessard<sup>2</sup>, Flyvbjerg et al<sup>3</sup>, Williams<sup>4-5</sup>). Megaprojects – defined by Flyvbjerg et al<sup>3</sup> as large infrastructure investments of around \$1billion (£500m) or more – are amongst the most complex with many suffering severe cost and time overruns. But not all mega projects fail. This paper compares two successful UK construction megaprojects, Heathrow Terminal 5 and the London 2012 Olympic Park, in terms of their complexity, and how these complexities were managed. Both projects were large and complex and subject to high levels of uncertainty, and both involved the development of unique governance structures and processes. Our analysis reveals common features but also some key differences in the approaches taken which provide lessons for the governance of future infrastructure projects and programmes.

**Key words:** Governance; Complexity; Megaprojects; Learning

## I. Introduction

Over the years there has been growing academic interest in how complexity affects the management of projects and past literature has suggested that increasing complexity in projects may be a significant factor in project failure (e.g. Morris & Hough<sup>1</sup>; Miller & Lessard<sup>2</sup>; Flyvbjerg<sup>3</sup>; Williams<sup>4-5</sup>). Megaprojects - defined by Flyvbjerg<sup>3</sup> as large infrastructure investments of around \$1billion (£500m) or more - are amongst the most complex. Cost overruns of 50% are typical and overruns of 100% not unusual. The reconstruction of the £798m Wembley Stadium project, for example, was 80% over budget and delivered four years later than originally planned. But not all mega projects fail and this paper examines what are considered to be two successful UK construction megaprojects, Heathrow Terminal 5 and the London 2012 Olympic Construction Programme, in terms of their complexity, and how these complexities were addressed in the governance and management of the two megaprojects.

Both projects were large and complex and subject to high levels of uncertainty, and both involved the development of unique organisational structures and processes. However, our analysis reveals differences in the approaches taken by those responsible for the management of these projects. In the following section we briefly examine the literature on project complexity. Next we move on to our empirical material first describing our research method

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<sup>a</sup> Centre for Research on Innovation Management, University of Brighton, BN2 4AT, UK

<sup>b</sup> School of Construction and Project Management, University College London, WC1E 7HB, UK  
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– case study comparison – and how we derived the data for analysis before presenting the two cases. We analyse the two cases in terms of similarities and differences in both their complexities and the approaches taken to cope with them in the light of the literature on project complexity. We end with some brief conclusions about the results and their generalizability to other complex infrastructure project settings.

## **II. What Does The Literature Say About Project Complexity?**

The inability to manage complexity has been recognised as a major factor in project failure for a number of years<sup>4</sup>. However, the concept remains ambiguous and ill-defined in much of the project management literature<sup>6</sup>. Efforts to define project complexity often make reference to systems theory and the idea that complex systems are decomposable into hierarchies of interacting components (e.g. Boulding<sup>7</sup> and Ashby<sup>8</sup>). Hirschman<sup>9</sup> was one of the first scholars to think of projects as systems, realising that the main challenge of delivering a complex project consisting of many interconnected component parts was not the size of the system itself but the difficulty in establishing a set of methods or a process to coordinate and adjust and fit the parts together into a coherent whole.

A number of scholars have used contingency theory as a way of defining project complexity. Baccarini<sup>10</sup> proposed two dimensions – ‘differentiation’ and ‘interdependence’ – to help distinguish between organisational and technological complexity. Differentiation refers to the number of components (task, specialists, and sub-components etc.) in the project system while interdependence is about the interrelatedness of the different components of the project system. Some authors have adopted the systems view to make distinctions between different types of project according to their complexity (e.g. Hobday<sup>11</sup> and Shenhar and Dvir<sup>12</sup>) relating this to the complexity of the product/outcome of the project. Projects can be distinguished by dimensions of system scope and technological uncertainty.

More recently Bosch-Rekvel, Jongkind, Mooi, Bakker and Verbraeck<sup>13</sup> have proposed a framework for characterising project complexity consisting of three main pillars – technical, organizational and environmental – to categorise large engineering projects. Another recent article<sup>14</sup> systematically reviewed the literature on project complexity to come up with a contingency framework consisting of five dimensions – structural, uncertainty, dynamics, pace and socio-political complexity project complexity. The dynamics and pace dimensions seem to add something new to the analysis of complexity. Dynamics refers to changes that might occur in the projects – which could be to specifications or goals or to the external or internal political environment – and they are broadly defined as a change in any of the other dimensions of complexity. Essentially pace refers to the rate at which the project needs to be delivered. We will see that this was an important feature in the two megaprojects we analyse below.

## **III. The Research Methods**

To understand how complex megaprojects can be successfully managed, we chose a comparative case study approach. Case studies of the two projects were built up based on extensive interviews with key persons using an approach based on engaged scholarship<sup>15</sup>. Data was gathered through interviews and official documents, presentations, contracts, reports and the trade press. For the Heathrow T5 case interviews took place over period of 20

months from June 2005 to January 2007. The London Olympics project interviews were conducted between December 2010 and September 2011 during the final stage of construction and handover to LOCOG (the London Organising Committee of the Olympic and Paralympic Games).

#### **IV. The T5 Project**

At the time of its execution the T5 project was one of the most complex construction projects in Europe, and the most complex and challenging project ever undertaken by Heathrow's owner BAA. All the construction work had to be carried out within a highly physically constrained environment whilst causing minimum disruption to the operational activities of one of the busiest airports in the world. The plans for T5 had been subject to the longest planning enquiry in UK history which laid down over 700 conditions including restrictions on delivery and working times. The project cost, £4.2bn, when set against its market capitalisation of around £6.8bn in January 2006, meant that T5 was an extremely risky undertaking for BAA.

##### **A. BAA's Novel Approach to managing T5**

During the long process of preparing for T5, BAA carried out systematic case study research into every major UK construction project over £1bn undertaken over the previous 10 years and every international airport opened over the previous 15 years and concluded that without a radically different approach the T5 project would cost over £1bn more than was affordable, would be two years late and result in six fatalities.

BAA's study identified two key areas that contributed to the poor performance of mega projects: the lack of collaboration among project partners; and, the client's reluctance to assume responsibility for project risk. BAA recognised that the risk entailed by T5 required a new approach to project management based on two core elements: integrated project teams and BAA's acceptance of the risk. These elements were used to create two documents used to manage T5: the T5 Handbook and the T5 Agreement – a novel type of cost-plus incentive contract based on the processes outlined in the T5 Handbook, which created a new set of behaviours that allowed member of projects to work under a set of collaborative rules for integrated project team working and partnering. These two elements of BAA's novel approach to project management were supported by three complementary innovations: a single digital model for project design and execution; pre-fabrication, pre-assembly and testing of components; just-in-time logistics. Together they represented a breakthrough in the management of mega projects.

##### **B. How did this approach help BAA manage complexity?**

To deal with the structural complexity BAA broke down the overall T5 project into 4 main areas: railways and tunnels, buildings, airport infrastructure and systems which went across the other three areas and involved the integration of all the IT and supporting systems. The single model environment meant that the same information was available to all parties involved thus helping with the information asymmetries that typically exist in large complex projects with multiple suppliers. The socio-political complexity in the project was addressed through the integrated project teams. These existed at the level of the 147 sub-projects and were made up of representatives from BAA and various Tier 1 suppliers: architects, designers, structural engineers, constructors, fabricators, specialist contractors etc. They were co-located, co-incentivised and co-responsible for the output of their projects. Where there were inter-dependencies between project teams these were recognised and managed at a

higher level. BAA made continuous efforts to break with traditional practices by reinforcing and rewarding team-based behaviours and fostering a culture of learning amongst suppliers based on 'soft' skills such as the trust and cooperation required to work 'constructively' on the project, rather than the hard skills of traditional contracting based on the commercial estimation of risks and making claims when problems arise.

Emergent complexity was dealt with by the use of re-imbursible contracts and incentives to innovate during the project and just-in-time logistics whereby the use of '*Projectflow*' software enabled teams to update daily what work had been completed so that only the materials needed for the next day's work could be lined up for delivery. Uncertainty was dealt with by earlier experimentation and standardisation of major components, by off-site testing to prove constructability and by a policy of not adopting untested technologies on site.

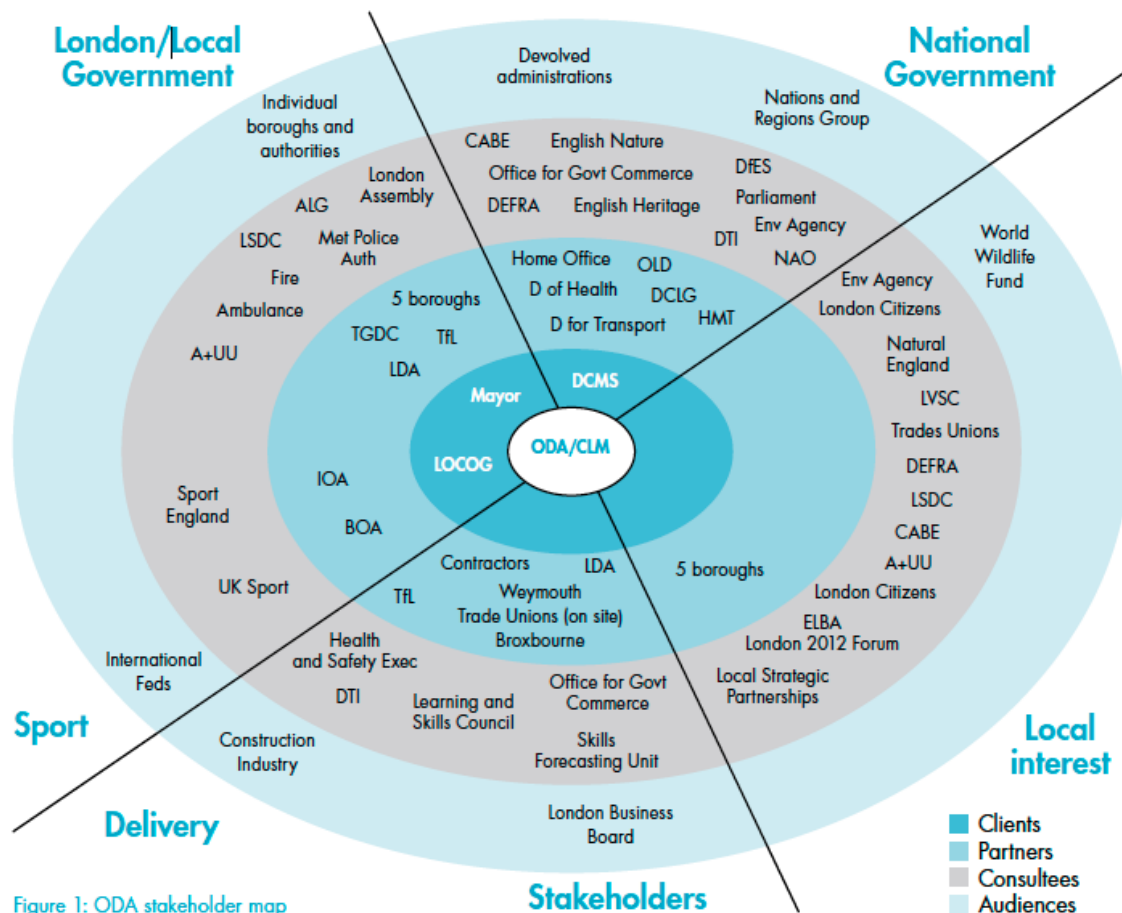
## **V. The London Olympics Construction Programme**

The London Olympics Construction programme was large and complex. It provided most of the venues for London 2012 and consisted of over 70 individual projects with many interdependencies between them such as common services and site logistics. The programme faced a number of other challenges, the major one being the immovable deadline for the programme; the opening ceremony for the Olympics was to take place on the 27<sup>th</sup> July, 2012. The organization set up around the Olympics involved multiple stakeholders (see Figure 1), some with conflicting objectives. The programme had dual objectives: delivering the venues and infrastructure for the Games and providing legacy benefits. There was a huge public sector investment in the Games and subsequently a very high public profile with the eyes of the world on the programme. These led to significant reputational risks for not only the organisations involved in the construction programme, but for the UK Government and the country as a whole. The over-riding imperative for the Olympics was that this was a programme that could not fail. It is against this background that the specific management approach was developed.

### **A. The Approach to Managing the London 2012 Olympics Construction Programme**

The London 2012 Delivery Team consisted of the London Organising Committee of the Olympic and Paralympic Games (LOCOG) and the Olympic Delivery Authority (ODA). LOCOG was a private company responsible for the planning, funding, preparation and staging of the London 2012 games with a £2 billion budget. The ODA was a public sector body responsible for developing and building the new venues and infrastructure for London 2012 and their use afterwards. The ODA had a £9.8 billion budget.

The ODA remit was "to deliver venues, facilities, infrastructure and transport on time for the London 2012 Olympic and Paralympic Games that are fit for purpose and in a way that maximises the delivery of a sustainable legacy within the available budget". So time, quality and cost were the prime focus of the delivery but there were other 'objectives' related to broader social and economic impact: Health, safety and security; design and accessibility; equality and inclusion; legacy; employment and skills; sustainability.



**Figure 1 ODA Stakeholder Map<sup>16</sup>**

The ODA programme was broken down into 50 individual projects in 6 different directorates: Infrastructure; Venues; Security; Logistics; Village; Transport. Each project had its own management structure and was led by a Tier One Contractor who was accountable for delivery. The ODA appointed a Delivery Partner, CLM (made up of a consortium of experienced construction companies: CH2MHILL, Laing O'Rourke, and Mace) to oversee the whole programme. Broadly speaking, CLM faced downwards to the various individual projects while the ODA faced upwards to the plethora of stakeholders such as LOCOG, various sports associations, many statutory bodies, and local and central Government. CLM was responsible for developing/specifying detailed project/programme management processes; administering the contracts with Tier one suppliers or equivalent; providing project assurance on each project; providing optioneering and problem solving expertise at the project level; managing the 'change' process; providing visibility of project performance for the programme level; collating performance at the programme level; managing the interfaces and dependencies between the various projects via integration management.

Some aspects –the five key management processes of up-front planning, project and programme monitoring, problem resolution, change management and integration management; the principles and targets related to health and safety and the other five priority themes; and the behaviours required to underpin the programme culture – were tightly controlled. Other aspects - how contractors would implement the principles and targets for H&S and the priority themes; approaches to procurement and contract (a recognised Tier One

contractor under design and build NEC3 C (target price with pain/gain) was adopted for the Olympic Stadium while design-led procurement was used for the Velodrome (given the desire for a ‘signature’ building) and a managed package strategy was adopted for the temporary venues); responses to external changes (e.g. the economic downturn in 2008 meaning the Athletes Village needed to revert to public funding) - were loosely managed to enable flexibility.

### B. How did this Approach Help the ODA Manage Complexity?

The breakdown of the overall programme into individual projects helped deal with the structural complexity. The socio-political complexity was dealt with by a very strong governance structure involving multiple layers of assurance and reporting (see Figure 2). The tight-loose approach enabled the ODA to achieve a highly consistent approach across the whole programme whilst facilitating flexibility to enable emergent complexity to be managed.

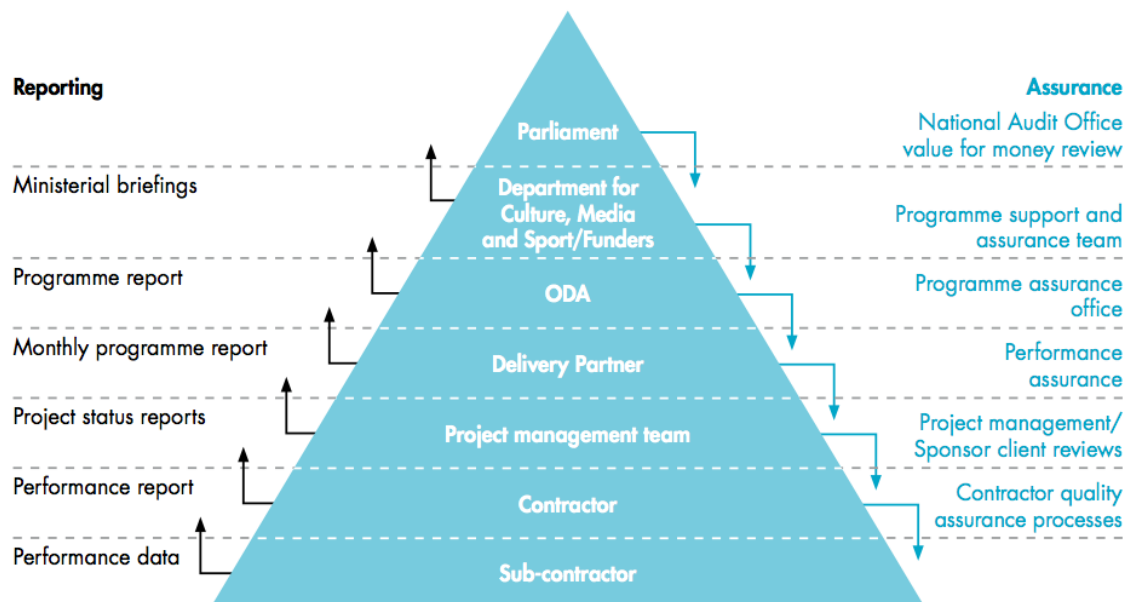


Figure 2 ODA Reporting and Assurance<sup>17</sup>

## VI. Some Brief Conclusions

While both projects were large and complex and subject to high levels of uncertainty, and both involved the development of unique organisational structures and processes there were differences in the approaches taken to govern these projects. In the T5 project, a single one-size-fits-all approach mandated by the client, BAA, established a consistent and standardised process and a common code of behaviour which was used uniformly on all sub-projects. In contrast, the ODA and its delivery partner, CLM, adopted a tight-loose approach to manage the Olympics construction programme which tried to strike a balance between consistent processes for managing change across the entire programme while adopting different approaches to individual sub-projects which allowed contractors the autonomy to adopt specific solutions to problem solving in individual projects.

In both cases time was an important factor. Both megaprojects had a long time to prepare for their openings and both had immovable end dates (for T5 this was imposed by BAA who insisted on an official opening date at end March 2008). Both were subject to a number of enablers which helped them be successful. In the case of T5 they were helped by the leadership of Sir John Egan who recognised that by learning from the experiences of other industries and applying these ideas, practices and technologies BAA could improve its own project processes. BAA recruited a senior team of talented people and employed leading consultants to prepare for T5 who had a deep knowledge and experience of business practices in other industries and/or a track record of successfully completing mega projects. Key enablers for the Olympics Construction Programme included existence of a well-resourced delivery partner; supportive contractual arrangements; and a supportive programme-wide culture. The division of roles between the ODA and CLM played a vital role in brokering between stakeholders and the contractors when it came to changes in requirements or changes necessitated by a project's situation. Despite this role separation, it is clear that the ODA and CLM worked very closely together – the ODA and CLM represented a “very intelligent client”. Both programmes were able to depend on the best efforts of the whole workforce. In the T5 case this was partly the result of the integrated team working and the co-incentivisation of suppliers but also on insistence in the T5 agreement that the best team would be made available for the project. In the case of the Olympics there was what has been described as the Olympic effect which meant that everyone was happy to be associated with the high-profile project and to seeing it succeed. Finally it should be noted that both projects had very large budgets with healthy contingency funds available for emergent needs. In conclusion we argue that the structures and processes adopted to successfully manage a megaproject should reflect the mix of complexity and uncertainty that surrounds the project.

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# Understanding The National Infrastructure Landscape

T.W. Broyd<sup>a</sup>  
A.Wescott<sup>b</sup>

**Abstract:** Infrastructure UK has been established within UK Government to coordinate the provision of National Economic Infrastructure, defined as energy, water, waste, transport and ICT. Co-ordination is not, however, easy. The lead for Government policy over the five infrastructure areas is shared across different Departments and arms-length bodies, sometimes with strong delineation and sometimes with wide cooperation. Policy is constantly developing and changes the overall landscape. To allow progress a snapshot of overall UK infrastructure policy across the five infrastructure areas has been developed, which provides a framework from which interdependencies between and among infrastructure policies and plans can be examined. This is enabling the identification of areas where a lack of discernible policy could lead to wider failures in interdependent sectors of UK national infrastructure or where synergetic opportunities should be captured. The author directed this work.

**Key words:** Infrastructure; Policy timelines; Interdependencies; Systems

## I. Introduction

Infrastructure UK was formed in 2009 as a unit within HM Treasury, with a remit to help prioritise and secure private sector investment funding in the UK's long-term infrastructure. It addresses the UK's national economic infrastructure (defined as energy, transport, water and flood management, waste and ICT) and is responsible at UK Government level for:

- co-ordinating and simplifying the planning and prioritisation of investment in UK infrastructure, and
- improving UK infrastructure by achieving greater value for money on infrastructure projects and transitions.

At the request of Infrastructure UK, Engineering the Future (EtF)<sup>1</sup>, the alliance of engineering professional bodies hosted by the Royal Academy of Engineering, has created a 'snapshot' of UK infrastructure policy across these five infrastructure areas. The information has been presented in the form of parallel timelines with a short narrative to explain the nature of interdependencies and why they have an important role in the development of government policy. The timelines provide a convenient and accessible way to assess policy and planning across the sectors of the UK's economic infrastructure. The linear presentation allows the reader to begin to visualise the interdependencies and opportunities and see, at a glance, where and when events resulting from lack of capacity, co-ordination or planning are likely to occur.

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<sup>a</sup> Bartlett Faculty of the Built Environment, University College London, WC1E 6BT, UK

<sup>b</sup> Institution of Civil Engineers, SW1P 3AA, UK  
<http://dx.doi.org/10.14453/isngi2013.proc.9>



These timelines provide a framework from which interdependencies between and among infrastructure policies and plans can be further examined. As the timelines evolve and the ability to analyse interdependencies develops it will enable the identification of areas where a lack of discernible policy could lead to wider failures in interdependent sectors of UK national infrastructure or where synergetic opportunities presented by those interdependencies should be captured.

The lead for government policy over the five infrastructure areas is shared across a number of Departments of State, sometimes with strong delineation and sometimes with wide cooperation. Policy is constantly developing and, as policies are consulted on and published, the overall landscape will change. The timelines should continue to provide an updatable tool that can chart the changing policy and delivery landscape. The authors of this paper acted as Steering Group Chair and Secretary of the EtF study team.

## **II. Understanding the Timelines**

The Infrastructure Timelines (Figure 1), are based on current known policies and plans (as set by government and by infrastructure operators and owners) and expert opinion from the EtF community. These are dynamic and evolving and, as such do not provide a completely comprehensive coverage of policies and plans.

They show significant planning in some areas of national infrastructure and a paucity of planning in others. They also show that planning in some infrastructure areas, such as ICT, has naturally much shorter time horizons as technological development and replacement is much more rapid than in other areas, such as transport. It is important to note that the issues driving the policies and plans vary across sectors, ranging from high level policy commitments such as carbon emission reduction, to commercial developments such as 4G mobile communications. As well as providing this visual mapping capability, the timelines can be used to identify where positive and negative interdependencies exist both within infrastructure sectors and across multiple sectors. Engineering the Future has and will continue to utilise the timelines to provide examples of where this may occur. In providing these examples and explaining when, where, how and why they may occur, interdependencies experts and engineers will assist decision makers with their current and future policy decisions.

The timelines are colour-coded to indicate where policies and plans appear to be in place (green), where the outcome of plans or delivery may be less certain or where policy statements are expected (amber) and where crises have been predicted unless action is taken (red). Beyond the known plans in the infrastructure sectors, there is some speculation by engineering experts (blue) which could impact on future plans. In many cases, the speculated developments represent areas where policy decisions will be required based on technological or behavioural developments that are currently far from certain; for example, if plug-in hybrid or fully electric vehicles come to dominate the UK market in the 2020s, a substantial increase in electricity generating capacity is likely to be required but there may also be opportunities to adapt infrastructure to take advantage of load spreading and vehicle-to-grid energy storage.

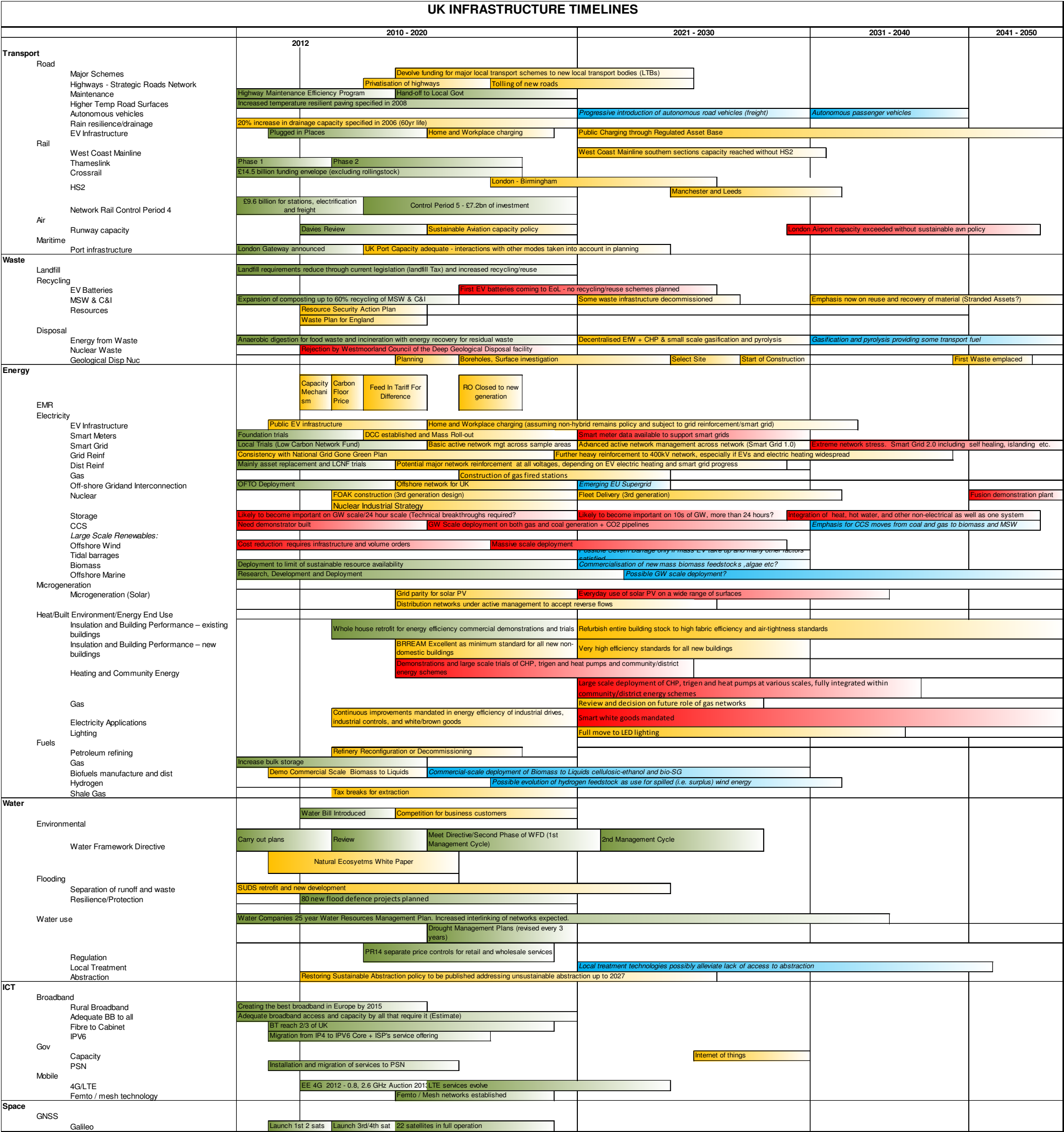


Figure 1: UK Infrastructure timelines.

### III. Interdependency Analysis – Methodology

EtF comprises a number of engineering institutions, which have contributed evidence to the research base for the infrastructure timelines. Staff from each institution has engaged with expert members through their various networks and expert groups to gain an insight into the policy and planning taking place across the five main infrastructure sectors. The analysis of intra sector and inter sector interdependencies used an Interdependency Planning and Management Framework (IPMF), which is being developed jointly by University College London and the University of Bristol<sup>2</sup>. This was employed within a workshop that brought together experts in the five key infrastructure sectors. Using the projects, policies and plans outlined in the Infrastructure Timelines, workshop delegates investigated both intra and inter sector interdependencies. Attendees discussed the intra sector interdependencies using five projects, policies or plans from each sector within the Infrastructure Timelines. They then undertook a similar activity, looking across the five sectors. As well as this, attendees indicated whether the interdependence was physical, digital, geographical and/or operational. Table 1 provides an explanation of these types of interdependence. The output of the workshop has been distilled and analysed into case studies, exemplified by those described below.

**Table 1 - Description of Infrastructure Interdependencies**

	Type	Description
<b>P</b>	Physical Interdependency	<ul style="list-style-type: none"> <li>• A transfer of resources, the output of one element becomes the input to another. This could be further refined to capture the nature of the transfer (e.g. Transfer of people).</li> <li>• A shared physical dependency between the two elements on a third resource (i.e. both elements consume the same fuel or use the same trained staff)</li> </ul>
<b>D</b>	Digital Interdependency	<ul style="list-style-type: none"> <li>• A cyber transfer of information. Again this could be refined to capture additional detail of the transfer.</li> <li>• A shared dependency between the two elements on the transfer of information from a third party source.</li> </ul>
<b>G</b>	Geographic Interdependency	<ul style="list-style-type: none"> <li>• The elements are located in the same place, or within close proximity.</li> </ul>
<b>O</b>	Organisational Interdependency	<ul style="list-style-type: none"> <li>• The elements are linked through a financial or logical mechanism.</li> <li>• The elements are organisationally linked by shared ownership, shared governance, or shared oversight.</li> <li>• The elements are mutually dependent on the services provided by a third party organisation</li> </ul>

### IV. Intra Sector Interdependencies

The following case studies highlight the types of intra sector interdependencies considered. Although the physical, digital, geographic and organisational interdependencies were available for analysis, almost 70% of the relationships discussed focussed on either physical or organisational interdependencies; therefore, these are the two interdependencies that will be addressed in the examples below.

### **A. Water Resource Management & Flood Risk Management**

Three separate entries on the Infrastructure Timelines were discussed by the water sector experts. The relationship between the flood defence schemes and sustainable drainage systems, the review of the sustainable licensing regime and the water company Water Resource Management Plans (WRMPs) were shown to have both physical and organisational interdependencies<sup>3</sup>. Flooding is generally considered a risk to multiple stakeholders, including homeowners, agriculture and businesses. In certain situations, storage infrastructure could be built to capture and store run-off, reducing flood risk and also providing a 'new' source of water. This source could be used to reduce river and groundwater abstractions undertaken by multiple stakeholders in a catchment or river basin. This has potential benefits for the ecological status of groundwater and rivers, but also provides a mitigation mechanism during periods of water scarcity as the reliance on groundwater and river abstraction would be reduced. In turn, this has an impact on the WRMPs produced by water companies. They have a potentially new source of water to include in their long term plans, which will also drive their short and long term infrastructure expenditure.

Managing the capture of this run-off will require organisational coordination as water companies, lead local flood authorities and the government will have to discuss planning, funding, building, ownership and maintenance arrangements. Thus far, the delivery of Sustainable Drainage Systems (SuDS) in the UK has been poor and guidance has yet to be provided by government. If drainage and storage systems, such as SuDS, are utilised more widely and effectively the government may be in a position to introduce a level of flexibility into its abstraction licence regime. It is important that the government engages with this process, as the changes it decides to make to licences may act as either incentives or barriers to this type of shared scheme.

### **B. Transport**

Organisational interdependence was considered one of the key areas for focus in the transport sector. In particular, collaboration was seen as important among the groups responsible for delivering strategic, multi-modal transport links in and around London and those responsible for highways funding and management. While there were a number of areas where positive interdependencies exist among these projects, there were considered to be two particular areas of focus.

First, the collaboration on Business Cases in each strategic transport project was seen as beneficial to the planning, design, delivery, governance and operation of the projects and policies. It was considered that there is clear value in an integrated transport approach, which should start at an early stage in projects such as the above. If the organisations involved in the stages of delivering these projects engage collaboratively then the multiple benefits can be identified early and actions implemented to achieve them.

Second, the under-utilisation of roads during certain hours was also raised as an area that could be addressed by improved collaboration and coordination among groups responsible for the delivery and management of these projects. Currently highways are available for night time movement of freight; however, local road policies often prohibit movement of freight. Delivery of strategic transport projects will require improved and more efficient movement of freight by the road network. Organisational collaboration in this situation would provide these stakeholders with a clearer view of the limitations of the current road policies, align their objectives to become mutually beneficial and allow them to resolve any issues in the

achievement of these objectives. As such projects develop it is also important that the transfer and movement of passengers is considered and integrated. This will require organisational coordination.

## **V. Inter Sector Interdependencies**

As with the intra sector discussions, approximately 70% of the inter sector interdependencies focussed on the physical and organisational interdependencies that exist. Figure 2 illustrates the full range of interdependencies that were discussed and captured at the interdependencies workshop. There are multiple examples of interdependencies contained within the table; however, the relationship between the energy sector and other sectors was seen as particularly important. Therefore, the energy sector provides an excellent case study with which to illustrate infrastructure interdependencies.

The energy sector provides necessary power to aspects of the ICT sector, such as cooling equipment, and relies on ICT for control systems. There is also a mutually beneficial relationship between ICT and Energy when the two sectors collaborate to create energy efficient equipment. Evidence from the workshop indicates that this partnership approach is currently inhibited by organisational and ownership issues that prevent best practice in the sharing of data. Smart metering, which has now been delayed in the UK by a further year, creates dependencies between energy and ICT. A high level of design solution and security is required of ICT in order to achieve functionality and public acceptance. Privacy is essential but at the same time it is beneficial for companies developing innovative solutions to home energy management to be able to access data with customer consent. A number of different parts of government need to work together with the industry to resolve these issues. While acknowledging the importance of confidentiality and ethics in data exchange, the workshop recommended that the appropriate sharing of data is incentivised to ensure the door is open for entrepreneurial activity.

Energy distribution and Transport assets can share the same physical space (route corridors) and the Energy sector provides the Transport sector with fuel (petrol and electricity for Electric Vehicles (EVs) and rail) and lubricants. The workshop on interdependencies identified the need to align Transport sector and Energy sector policies in order to avoid a potential failure from a lack of interdependency planning. This failure was seen as particularly concerned with the possible increase in electricity demand should there be a significant switch to electric vehicles and the government policy to electrify the rail network, which is currently underway and highlighted on the Infrastructure Timeline (Figure 1). There are particular transport projects where electrification of a small part of a network will allow use of electric traction for rail freight all the way through the network. This would have a wider economic benefit. While there is some suggestion that domestic EV charging may take place in off-peak periods, there is still a need for interdependency planning in this area. There is a need to ensure policy concerning uptake of EVs and the development of supporting infrastructure reinforces policy concerning energy use and vice-versa. There is also a requirement for the development of a recycling and/or waste policy for spent EV batteries. The infrastructure timelines show that there is currently no policy in place to reuse or recycle EV batteries as they begin to come to their End of Life period in approximately 2015.



Energy	P: Energy sector provides <u>necessary</u> electricity for operating and cooling ICT sector equipment (e.g. Server Farms)	P: (1) Energy sector provides <u>necessary</u> fuel (hydrocarbons) and lubricants to Transport sector; (2) Energy sector provides <u>necessary</u> electricity for electrified rail and Electric Vehicles in the Transport sector	P: (1) Energy sector is a source of general Waste transferred into Waste sector; (2) Energy sector is a source of Nuclear Waste	P: (1) Energy sector activities (e.g. Shale Gas) can transfer pollutants which contaminate ground water; (2) Energy sector provides <u>necessary</u> electricity to Water sector for pumping etc.; (3) Energy sector requires Water for cooling plant
		G: Co-location. Energy sector utilities and Transport sector assets share physical space		
	O: (1) Energy and ICT sectors can collaborate to create energy efficient equipment; (2) Energy and ICT sectors collaborate on sharing data (hindered by ownership issues)			O: Energy sector requires payment from Water sector for electricity provided to power pumps
P: ICT sector provides <u>necessary</u> resources to Energy sector	ICT		P: ICT components in space can become or produce space Waste	P: ICT sector requires protection from flooding provided by Water sector
D: ICT sector provides resources for Smart Grid, Smart Metering, Demand Management, Control and Billing to Energy sector		D: (1) ICT sector can <u>potentially</u> provide digital capability to reduce need for physical Transport; (2) ICT sector provides resources and capability for Transport sector activities: (a) Congestion charging (b) "Boris bikes" (c) Multimodal journey management (d) Global positioning (e) Comms. (f) Tracking (g) Stock control (h) Road use charging	D: ICT sector provides the capability for Waste and recycling 'tagging'	D: (1) ICT provides the capability for Smart Metering and management of/within Water sector; (2) ICT provides the capability for digital control of/within Water sector
		G: (1) Some ICT Plants and Services are geographically linked to the Transport network; (2) Co-location of some ICT physical assets (e.g. telecoms cables) and some Transport assets (e.g. roads)		
O: (1) ICT sector provides <u>necessary</u> control and communications systems to Energy sector during set-up; (2) ICT sector and Energy sector can collaborate to reduce ICT energy footprint; (3) ICT and Energy sectors collaborate on sharing data.		O: (1) ICT sector provides data management capability to Transport sector; (2) ICT sector and Transport sector collaborate on sharing data; (3) ICT sector provides capability for Transport sector to perform Logistics Route Planning; (4) ICT sector provides capability for general operational usage within Transport sector	O: ICT sector and Waste sector collaborate on sharing data	O: ICT sector and Water sector collaborate in sharing data
P: (1) Transport sector provides the capability to move Shale Gas; (2) Transport sector provides the capability to move fuel to power stations; (3) Transport sector <u>could</u> transfer excess heat from vehicle tunnels into Energy sector	P: Transport sector provides capability for JIT delivery for ICT sector	Transport	P: (1) Transport sector provides the <u>necessary</u> capability to move Waste; (2) Transport sector creates Battery Waste which requires disposal	P: (1) Transport sector can <u>potentially</u> provide: (a) an obstruction to Water or (b) facilitate its transfer; (2) Permeability of materials used to construct Transport sector assets can affect flood risk
D: Transport and Energy sectors share intelligence information	D: Transport sector <u>relies</u> on ICT sector for Road use charging capability.			
G: Co-location of Transport and Energy assets				G: Co-location of Transport and Water assets to provide utility corridor
O: (1) Transport sector <u>requires</u> network for Electric Vehicle (EV) charging; (2) Sector policies must be aligned to achieve goals (i.e. uptake of EVs and reduction in domestic energy use)			O: Transport and Waste sectors can collaborate to change behaviours on emissions (Nudge, wink, hug etc.)	O: Transport and Water sectors can collaborate on flood management planning rules
P: (1) Waste and by-products can <u>potentially</u> provide a resource for the Energy sector including processes such as Anaerobic digestion; (2) Waste can <u>potentially</u> provide a source of rare Earth metals needed by the Energy sector		P: Waste sector <u>requires</u> Transport sector for (1) Movement of hazardous waste; (2) Movement of general waste; (3) Movement of specific materials that cannot be disposed locally (e.g. Japanese knotweed)	Waste	P: (1) Waste sector can <u>potentially</u> produce contaminated water which is transferred to the Water sector; (2) Waste in landfill can <u>potentially</u> cause more Water runoff
				G: Co-location of Waste facilities and Water resources can <u>potentially</u> result in ground water contamination
O: Waste disposal plans may need to be in place before new power stations are approved (especially Nuclear)		O: Separation of Waste at source and separation of Waste at a dedicated facilities have different transport needs (and affect Efficiency versus Quality)		
P: (1) Water provides a <u>potential</u> means to generate electricity; (2) Water provides a <u>necessary</u> means of cooling Energy plant; (3) Water provides a <u>potential</u> means of Energy storage; (3) Water sector may <u>require</u> Energy for Bulk Water Transfer		P: Water sector provides flood protection for Transport sector assets	Water	
	D: Water sector <u>relies</u> on ICT Sector for Smart Meters and Demand Management			
		G: (1) Co-location of Transport assets and Water sources can increase the risk of flooding; (2) Water utilities can disrupt Transport network by digging up roads; (3) Water sector utilities can degrade road system due to sub-standard re-installment		
O: Water sector provides payment to Energy sector for Pumping	O: Water sector collaborates with ICT sector for real time data exploitation to maximise efficiency, energy use and resilience			

Figure 2: Infrastructure Interdependencies Generated by the Workshop.

Energy is also important to the water sector as electricity is required for pumping and many waste water processes. This key relationship is emphasised by the successful attempts by some water companies to generate their own electricity from renewable sources or from waste by-products generated by certain processes. Water is also required for cooling within a number of electricity generating processes. This could be challenging in the future, particularly in situations where inland water sources are required for cooling purposes. According to the Climate Change Risk Assessment, lower river flows in summer caused by climate change may impact on the amount of freshwater inland energy stations can abstract for use in cooling<sup>5</sup>. This should be a significant factor in the government's approach to reviewing the abstraction licence regime.

Shale gas extraction is viewed by government as a potential source of energy to improve the UK's energy security. Although the viability of shale gas extraction is still unclear, there is interdependency with water that must be considered carefully. Water is required as part of the fluid used in the hydro-fracturing process. The process produces a brackish by-product that has to be disposed of carefully. Recycling wastewater where possible would reduce the volumes of wastewater in need of disposal as well as reducing the burden on freshwater abstractions. Wastewaters can be diluted with freshwater and then reused in subsequent fracturing operations<sup>6</sup>. It is important that the necessary parts of government collaborate on the development of fracking and that regulation is utilised to manage the water and environmental risks concerned with the process.

## **VI. Conclusions & Recommendations**

The study described in this paper demonstrates the initial parts of an interdependencies toolkit which will allow improved understanding of potential synergies across multiple infrastructure sectors. Comparing policy, planning and project timelines across the infrastructure timelines should enable government departments to collaborate to identify the interdependencies that their particular policies may encounter elsewhere. The identification of these interdependencies should allow government departments to work together in order to mitigate any future issues that may occur and plan policies that are aligned. The infrastructure timelines should continue to evolve as a dynamic visual aid to inform the development of government policies.

Major recommendations include:

- Policy makers should utilise interdependency analysis and the Infrastructure Timelines to plot current and future policies and align policy development where necessary.
- Government departments should improve the coordination and communication between and among regulators and asset owners.
- Further research and implementation of interdependency analysis is required.

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# **A Framework for Integrated Energy Systems, Infrastructure and Services Optimization with Visualization and Simulation Platform for Low-carbon Precincts**

Aumnad Phdungsilp<sup>a\*</sup>

Ivo Martinac<sup>a</sup>

Tuan Ngo<sup>b</sup>

**Abstract:** The energy informatics can be enhanced to support decision-making, communication and benchmarking of the energy performance both in design and operational phases. To enable engineers, developers and policy-makers to better understand the implications of energy systems and services, computer-generated visualization is a powerful tool to inform a range of technological options and to analyze the effects of energy system strategies. Visualization increases the transparency of results and the understanding of interactions between users and energy systems. This paper presents a novel conceptual framework for integrating energy systems, infrastructure and services optimization with a visualization and simulation platform. It focuses on the development of a tool for low-carbon energy systems and high quality energy services at precinct scale. The paper describes the vision and architectural design for the integrated framework. It is expected to serve as a next generation approach to managing energy services, carbon emissions and efficient resource use in the built environment. This will help to deliver new environmentally sustainable infrastructure and achieve carbon neutrality in urban development.

**Key words:** Energy Systems and Services; Low-carbon Precincts; Simulation; Visualization

## **I. Introduction**

There is a growing interest in improving the energy performance of urban areas so that environmental impacts are reduced while maintaining economic competitive capacity and quality of life. In recent years, different cities, local authorities and developers have shown the interest in virtual 3D urban models. Some of the experiments have been applied for applications in urban planning. There is a need for a tool that offers the holistic energy visualizing at the urban district or precinct scale, not only from the building perspective. This will enhance the understanding of the urban energy systems and the analysis of energy competitions between resources and services.

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<sup>a</sup> School of Architecture and the Built Environment, Royal Institute of Technology, Stockholm, Sweden

<sup>b</sup> Department of Infrastructure Engineering, The University of Melbourne, Australia.

\*Corresponding author: Aumnad Phdungsilp [aumnad.phdungsilp@byv.kth.se](mailto:aumnad.phdungsilp@byv.kth.se)  
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A number of studies have been done on the development of simulation-based optimization modeling tools for decision-making processes in the area of built environment. However, most of the previous studies are focused on a building scale. As noted by Ref. 5 there is a need for tools that can help to assess and design more efficient urban energy systems. Some existing tools include SUNtool,<sup>1</sup> SynCity,<sup>2</sup> EnerGIS,<sup>3</sup> and DESDOP.<sup>4</sup> Ref. 8 stated that the realization of integrated urban design tools requires advanced multidisciplinary modeling, interoperability of computation models and collaborative research for the optimal integration of energy systems. A brief review suggests that modeling tools can be differentiated according to their contributions and systems (energy, water and land-use) addressed.

This research was motivated by the need to optimize energy systems to achieve a carbon neutral urban development and to visualize the findings in a 3D environment. This paper focuses on the development of an optimization tool for integrated energy systems, infrastructure and services. The integrated platform would offer a next generation approach to assist the design, analysis and evaluation of energy, carbon emissions and resource consumption in the built environment.

## **II. Conceptual Framework**

The framework developed in this research is based on techniques of three domains: building energy modeling; energy systems modeling; and geographical information systems (GIS). The conceptual framework of the research is presented in Figure 1. Urban systems are complex issues, thus a combination of these techniques enables to visualizing the demand of energy services, cost and emission indicators resulting from different system configurations integrating into urban infrastructure. Visualization increases the transparency of results and creates a better understanding of the interactions between different sub-systems. This is expected to provide a means for engineers to handle multiple parameters elements in the planning processes allowing a large number of stakeholders with different interests such as architects, developers, environmentalists, and local authorities, to discuss the issues and to find an optimal solution regarding supplying energy services. It is expected to serve as a powerful tool to support decision-making, performance assessment, communication and benchmarking.

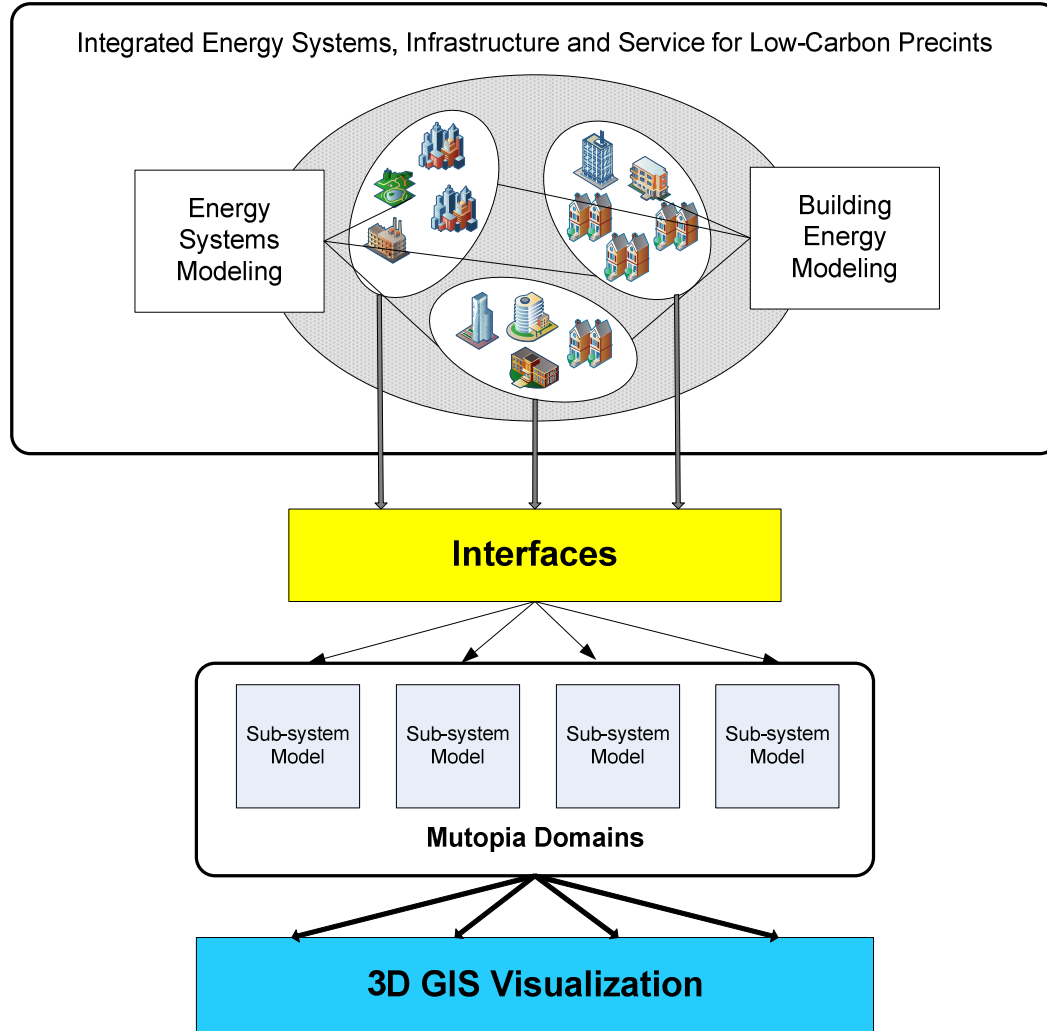
According to Figure 1, building energy performance can be modeled with a variety of building energy performance softwares such as TRNSYS, EnergyPlus, DOE2.1E, IDA ICE.<sup>5,6</sup> Hourly load profiles include demand for heating, cooling, hot water and electricity. GIS is today commonly used tool in urban planning. It has been integrated with energy and environmental models for the development of sustainable urban energy systems.<sup>3,7</sup> In this research, we are developing the energy systems and services optimization model to provide information services integrating with other sub-models within the framework. Therefore, this paper explains briefly the simulation-based optimization energy systems that currently being developed at our division to find a set of optimal combinations.

In designing energy systems, there are often conflicting objectives between different stakeholders involved in the planning process. Thus, we are employing multi-objective optimization techniques to find a set of optimal solutions. For example, typical objectives in the energy systems planning are to minimize the life cycle cost and CO<sub>2</sub> emissions. These objectives

are naturally competitive: the (first) cost of environmentally friendly energy technologies often exceeds the corresponding cost of conventional solutions, at the same time as the energy-efficient technologies may be less environmental friendly than other technologies that are less efficient. The European Energy Performance of Buildings Directive recast targets two objectives: the primary energy consumption and the life cycle cost to be assessed to find the environmental and economic impacts of buildings.<sup>8</sup> Our interest in this research is to maximize exergy efficiency while minimizing the environmental impacts of energy systems.

The solution of the multi-objective problem is a set of non-dominated solutions, known as the Pareto set with the plot of Pareto optimal solutions referred to as the Pareto front. This will give decision-makers the opportunity to assess the trade-off between conflicting objectives. Multi-objective optimization problem can be solved by several optimization algorithms, for example multi-objective genetic algorithms such as NSGA-II (elitist non-dominated sorting genetic algorithm). The algorithms can be solved by either customized or generic optimization tools, for example MultiOpt,<sup>5</sup> MATLAB,<sup>9</sup> DAKOTA,<sup>10</sup> and MOBO.<sup>11</sup>

This research is developed to interface with the MUltopia ([www.mutopia.unimelb.edu.au](http://www.mutopia.unimelb.edu.au)) simulation platform to provide decision-making support, communication and benchmarking of the energy performance of low-carbon precincts. MUltopia is an information technology-based platform tool for supporting the assessment of urban sustainability metrics at different scales. It is an urban design modeling and visualization platform, which displays in 3D the actual appearance of an urban development. It operates in a virtual environment based on 3D geospatial technologies and capable of visualizing inputs (energy, infrastructure and transport) and outputs (such as energy use and carbon emissions). It provides an online visualization platform that represents data and results in 3D environment, including the provision of real-time, effective and high quality visual representations of urban scenes and objects. Thus, MUltopia enables stakeholders from different disciplines to collaboratively test innovative concepts, tools and processes in a single virtual environment ([www.mutopia.unimelb.edu.au](http://www.mutopia.unimelb.edu.au)). The link between energy systems modeling and MUltopia enables the development of strategies for visualizing the energy performance of buildings and precincts. It is expected to serve as a powerful tool for creating a better understanding of the interactions between different sub-systems. It should be noted that the goal of this research is to develop the energy systems and services optimization (multi-objective optimization algorithm) that can be integrated to MUltopia in order to evaluate a set of design variables which provide the optimum solution to supply energy services for achieving a carbon-neutral urban development.



**Figure 1.** Conceptual framework of this research

### III. Steps Toward the Framework Implementation

Energy systems are connected with different supply technologies to provide building services. Buildings have been the core of built environment research while the interest in 3D geographic tool is growing. By way of demonstration, the framework will be applied to a new urban development project—Albano which is located in Stockholm, Sweden. The purpose of the developed framework is to implement for evaluating and visualizing the results of the energy systems modeling. Albano is a university campus area under in Stockholm, Sweden currently under development to provide approximately 150,000 m<sup>2</sup> of educational and research facilities, housing for students and visiting scholars, and premises for commercial services such as restaurants. The overall goal is for the area to serve as a living laboratory for sustainable urban development in which different innovative concepts can be tested. Albano aims to achieve a neutral balance in CO<sub>2</sub> emissions caused by energy systems by 2030.

Thus, Albano will be a hypothetical test site. It is expected that all buildings are to be built to passive house standard. The energy system has to supply energy services to meet the demand. Therefore, it is a vital importance to understand detailed information on local energy demand so as to achieve a satisfying performance of the energy system. The energy systems model requires hourly energy demand profiles for each building as input. The hourly energy demand profiles are obtained through a building energy performance program named IDA ICE (IDA Indoor Climate and Energy).<sup>12</sup> We are interested in a cluster of buildings, so taking one representative building for each of the building type. Then, we create energy load profiles of a representative day for each month and assume that each day in a month follows the same demand pattern of the representative day, consisting of the electricity and heating demand (kW). The demand pattern of a representative day is averaged though that month. Moreover heating is not required during the summer, and cooling is neglected.

The case study will be tested on the question: what is the impact of installing local combined heat and power (CHP) plants in comparison to investing solely in electrified heating? To address this question two scenarios will be modeled and compared to a reference case.

- Reference: conventional energy system, with heating demand from district heating network and electricity purchased from the national grid.
- CHP: an energy system that contains only CHP technologies, with generation in a building cluster and distribution permitted between buildings in that cluster.
- Electrification: an energy system that install distributed energy resource (DER) system, such as heat pumps, PV and wind turbines, with distribution permitted between buildings in a cluster.

The application of the optimization model allows for the analysis of several issues, for example analyses of economic and environmental impact of the energy systems. The main outputs from the analytical model can be visualized in 3D through the use of MUTOPIA platform.

#### **IV. Conclusion**

This paper aims to present the development of a tool integrating the optimization of energy systems and services for urban districts, with the MUTOPIA visualization and simulation platform. The tool is intended to be tested on the case of the Albano Campus, a new urban development in Stockholm, Sweden. A series of Pareto optimal solutions is expected to identify, which can help to get a better understanding of the trade-off relation between different objectives. The proposed framework combines interoperable models for energy systems design and evaluation and connects with information systems for visualizing the results and monitoring. This will allow analysts to go beyond the traditional work on urban energy modeling that focused on computing technical aspect and related issues. In our view, the integrated energy systems, infrastructure and services optimization with visualization and simulation platform has the potential to serve as a tool for decision-making in the context of low-carbon urban development. It will allow to inform a range of technological options and to analyze the effects of energy system strategies.

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# A Systems-based Approach to Creating Value from Infrastructure Interdependencies

Dr Ges Rosenberg<sup>a\*</sup>  
Dr Neil Carhart<sup>b</sup>

**Abstract:** Current planning and appraisal processes treat infrastructure as discrete, sector-specific assets, and as a consequence can fail to identify and exploit potentially valuable interdependencies. Similarly, these silo-based approaches are unable to identify potentially hazardous and costly interdependencies in a systematic manner. A major challenge then for providers of modern infrastructure, is to realise the innovative opportunities in interdependencies, and so increase value-for-money, sustainability and resilience. To overcome this, it is necessary to recognise that real-world infrastructure ‘systems’ are highly interconnected, both with each other and with the socio-economic and natural systems in which they are located. This paper presents a focused set of the findings from a research partnership between the University of Bristol and University College London, sponsored by HM Treasury in the UK. It proposes an ‘open-systems’, cross-sectoral approach to create and manage beneficial infrastructure interdependencies, and comprises a framework of principles: ‘stewardship’, ‘shared-governance’ and ‘interdisciplinarity’; and associated systems-based tools. These have been applied to four case studies relating to the UK’s National Infrastructure Programme, three of which are summarized in this paper.

## I. Introduction

Infrastructure fulfils a unique and vital role in society, delivering goods and services both to private citizens, public organisations and private companies, and thereby underpins societal and economic activity. The need for more and better infrastructure is an issue that affects all countries. Current estimates suggest a global need for infrastructure investment of \$57 trillion by 2030 simply to keep pace GDP growth<sup>1</sup>, and National Infrastructure remains “a major determinant of growth and productivity”, and an instrument which governments look to for geographically balancing economic growth and social development.

In the UK, infrastructure development over the last 150 years has been conceptualised and treated for the main part as a series of complicated technical challenges. The focus of the professions (engineers, architects, project managers and economists) has been on commissioning

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<sup>a</sup> Research Fellow, Systems Centre & Department of Civil Engineering, University of Bristol, Bristol BS8 1UB, United Kingdom ges.rosenberg@bristol.ac.uk

\* Corresponding author

<sup>b</sup> Research Associate, Systems Centre & Department of Civil Engineering, University of Bristol, Bristol BS8 1TR, United Kingdom

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and operating individual infrastructure assets; each of which has been specified and appraised at a given juncture against a current perceived need, for a tightly defined life-expectancy, and then designed, built and operated by an individual industrial sector. As a result, the National Infrastructure Plan 2011<sup>2</sup> characterises the UK's historical approach to the development of national infrastructure as being "fragmented and reactive", noting that "opportunities to maximise infrastructure's potential as a system of networks have not been exploited." There has therefore been a general failure to identify and capture potentially valuable infrastructure interactions, coupled with a lack of *systematic* identification of potentially hazardous and economically damaging interdependencies. It is also evident that interdependencies, and the attendant benefits and costs, frequently emerge without prior intent to identify or utilise them, even in cases where they may reasonably have been forecasted.

In common with other developed countries, the UK's infrastructure is ageing, frequently beyond its expected design life, added to which socio-economic demands placed upon it are rapidly increasing and changing. This has led to calls for investment to modernise and expand the UK's infrastructure asset base<sup>1-5</sup>. However, ownership of infrastructure and patterns of governance are typically segmented into regulated industrial sectors, adding both institutional and policy barriers to resolve if a more integrated approach is to be implemented.

This research was completed in August 2013 by the University of Bristol's Systems Centre and The Bartlett, University College London<sup>6-10</sup>. Its scope was to investigate an open systems-based approach to creating and managing interdependencies that could sit alongside, and build upon, the existing project appraisal and evaluation process set out in the HM Treasury Green Book<sup>12, 13</sup>. The top-level requirements for the Interdependency Planning and Management Framework (IPMF) were identified<sup>6</sup> as:

1. Provide a systematic process for identifying and handling infrastructure interdependency, including both beneficial interdependencies (benefits and opportunities) and adverse interdependencies (risks and additional costs);
2. Support a process of continual improvement in the handling of infrastructure interdependencies;
3. Support the collective governance of infrastructure;
4. Provide a holistic approach to the measurement and assessment of options;
5. Provide a robust tool to support decision making;
6. Integrate with the existing guidance for project appraisal<sup>12, 13</sup>;
7. Facilitate a broad-based approach to stakeholder engagement;
8. Be equally applicable to new and legacy infrastructure;
9. Recognise practical constraints for the purposes of implementation.

This paper presents a focused subset of the findings from the full research programme. It concentrates on the engineering systems toolset used to implement the IPMF for three of the case study applications: Phase 2 of the UK's High Speed 2 Rail project<sup>5</sup>; the Lower Thames Crossing<sup>14</sup>; and Engineering the Future's National Infrastructure Timelines project<sup>15</sup>. Although the framework has been used to identify, represent and analyse both positive (beneficial) *and* negative (adverse) interdependencies, this particular paper focuses solely on how the approach and tools can be used to innovate and create value from beneficial infrastructure



interdependencies. The framework has been developed as a generic set of principles and processes, and hence a wide range of planning and systems engineering toolsets could be deployed to implement the approach. Typically these might include use case analysis, systems dynamics modelling, influence diagramming, scenario planning, stakeholder analysis, multi-criteria assessment (MCA), uncertainty management techniques, impact assessment and sustainability appraisal frameworks<sup>6,16-19</sup>. For the case studies presented, a matrix mapping approach (after Lano<sup>20</sup>) was used to implement the framework.

## II. Development of the Interdependency Planning and Management Framework

At the core of the resulting framework is a set of systems thinking principles, processes and tools which aim to drive infrastructure proposers and delivery teams to look for a) beneficial interdependencies with other infrastructure and policies (synergies), and b) problematic dependencies (systemic vulnerabilities or conflicts) to be managed. By exploring, and potentially expanding the boundary, planners and engineers are free to identify the principal ‘soft’ and ‘hard’ systems with the potential to interact with the core infrastructure system(s) being developed. The approach requires policy makers, economists, planners and engineers to adopt four key principles:

1. That infrastructure development requires a holistic, open systems view of infrastructure, and hence recognise and adopt a ‘system of systems’ perspective.
2. That all ‘hard’ infrastructure systems are developed within a framework of ‘soft’ systems comprising policies, regulations, processes and practices, coupled with the institutions, organisations and people that define and implement them.
3. To question and explore the accepted and/or perceived system boundary for an infrastructure development in order to engage with a wider range of stakeholders and create the potential for innovative project scoping and design options.
4. To develop a strategic governance or ‘stewardship’ approach for infrastructure. This requires a shift away from an individual asset management perspective, and instead requires a wide range of institutions and enterprises to collaborate in developing a coherent framework of policies, plans, processes and institutions to guide future infrastructure investment and planning.

The proposed framework is implemented through three groups of activities: 1) Problem Structuring; 2) Measurement and Appraisal; and 3) Creating Stakeholder Understanding. These activities are undertaken iteratively and in some cases concurrently, and are informed by an evolving and maturing knowledge base in interdependency planning and management<sup>21</sup>.

In the context of the framework (see Figure ), **Problem Structuring** is defined by eight sub-activities:

- 1) Explore the system boundary and policy context<sup>22,23</sup>. This preliminary activity formally embodies the three principles above into the framework process. It provides the opportunity for creative thinking during infrastructure planning, appraisal and design, and promotes participation from a broad group of relevant stakeholders.

- 2) Establish and frame the core development needs. This is necessary to ensure that criteria of success for the core development goal can be established, and therefore that the cumulative effects of beneficial and adverse interdependencies can be appropriately framed and assessed in the appraisal process.
- 3) Explore the boundary and context to the infrastructure needs. It is necessary creatively and systematically to search and reveal the relationships between the defined need for the core intervention and other socio-economic and environmental needs and policy goals which comprise the 'context'.
- 4) Identify the architecture of the infrastructure network. The systems architecture provides a high-level, conceptual model that depicts the structure of a given system, and the interactions it has with other hard and soft systems. This captures and represents the planned development and its relationships with other infrastructure. It allows for the general nature of the infrastructure development to be communicated with stakeholders, and provides a platform for identifying interdependencies.
- 5) Identify interactions with additional socio-economic and environmental needs. Engagement with a broad spectrum of infrastructure stakeholders is important to identify both core and additional higher-level needs which could be met by the core infrastructure development.
- 6) Identify opportunities to develop beneficial interdependencies<sup>24</sup>. This may occur when defining the infrastructure need, when setting the objectives and appraising a project, and during implementation and post-project evaluation and upgrade.
- 7) Identify risks from adverse interdependencies. The risks from adverse interdependencies<sup>25</sup> should be identified throughout the planning, design, implementation and operation of the infrastructure, and it is particularly beneficial to apply them early on before project goals have been substantially set.
- 8) Define objectives for interdependency planning and management. Planning of options can now be guided by decisions over which beneficial interdependencies should be incorporated into the scope of core infrastructure project, as supported by the engineering analyses and economic appraisal.

The Measurement and Appraisal leg of the framework comprises three activities:

- 1) Establish criteria to validate interdependencies. The value of the beneficial interdependencies should be assessed and validated, for example using a Multi-Criteria Analysis (MCA)<sup>16</sup>. A range of holistic appraisal tools have been developed, generally based around PESTLE<sup>12</sup> and other sustainability checklist approaches, and these provide a useful means of identifying appropriate decision criteria. Similarly criteria for assessing the adverse impacts from negative interdependencies will be need to be established at this stage in the process, for example defining the levels of probability and impact commonly used in probability-impact approaches to risk assessment<sup>26</sup>.
- 2) Gather evidence and appraise interdependencies. Evidence to support the appraisal of interdependencies is compiled throughout the stages of: 1) exploring the systems boundary and context; 2) the creation of stakeholder understanding; and 3) during the identification of positive and negative interdependencies. The approach to appraising

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<sup>12</sup> Political, Economic, Social, Technological, Legal and Environmental (PESTLE)

interdependencies should be consistent with the overall appraisal process for the main project.

- 3) Review business case against maturity of interdependency management. Criteria setting out levels of maturity in interdependency planning and management would need to be established in areas such as willingness to collaborate; openness of contractual and commercial management; capability to manage complex cross-sectoral projects; risk appetite of investors; and engineering design and economic appraisal toolsets. The business case for any proposed interdependency should be reviewed against a framework of organisational maturity criteria to ensure there is sufficient capability and willingness in partnering organisations and industrial sectors to deliver planned interdependencies successfully.

The successful application of the two stages above relies upon the engagement of a wide selection of stakeholders, and processes to Create Stakeholder Understanding as follows:

- 1) Identify cross sector stakeholders for potential collaboration. Effective and *early* engagement with a diverse but relevant set of stakeholders<sup>27</sup> is critical if a more comprehensive and robust set of interdependencies is to be identified, appraised and adopted. Early engagement will reduce the risk of major design changes being required subsequently, discourages the premature adoption of solutions dominated by one specific technology or sector, and help to avoid the premature discarding of options.
- 2) Develop interdependency planning and management practice. The IPMF recognises that there is a need to embed a context-dependent learning process that can inform the development of strategic policy, governance/stewardship and valuation of infrastructure and associated interdependencies on a continual basis.

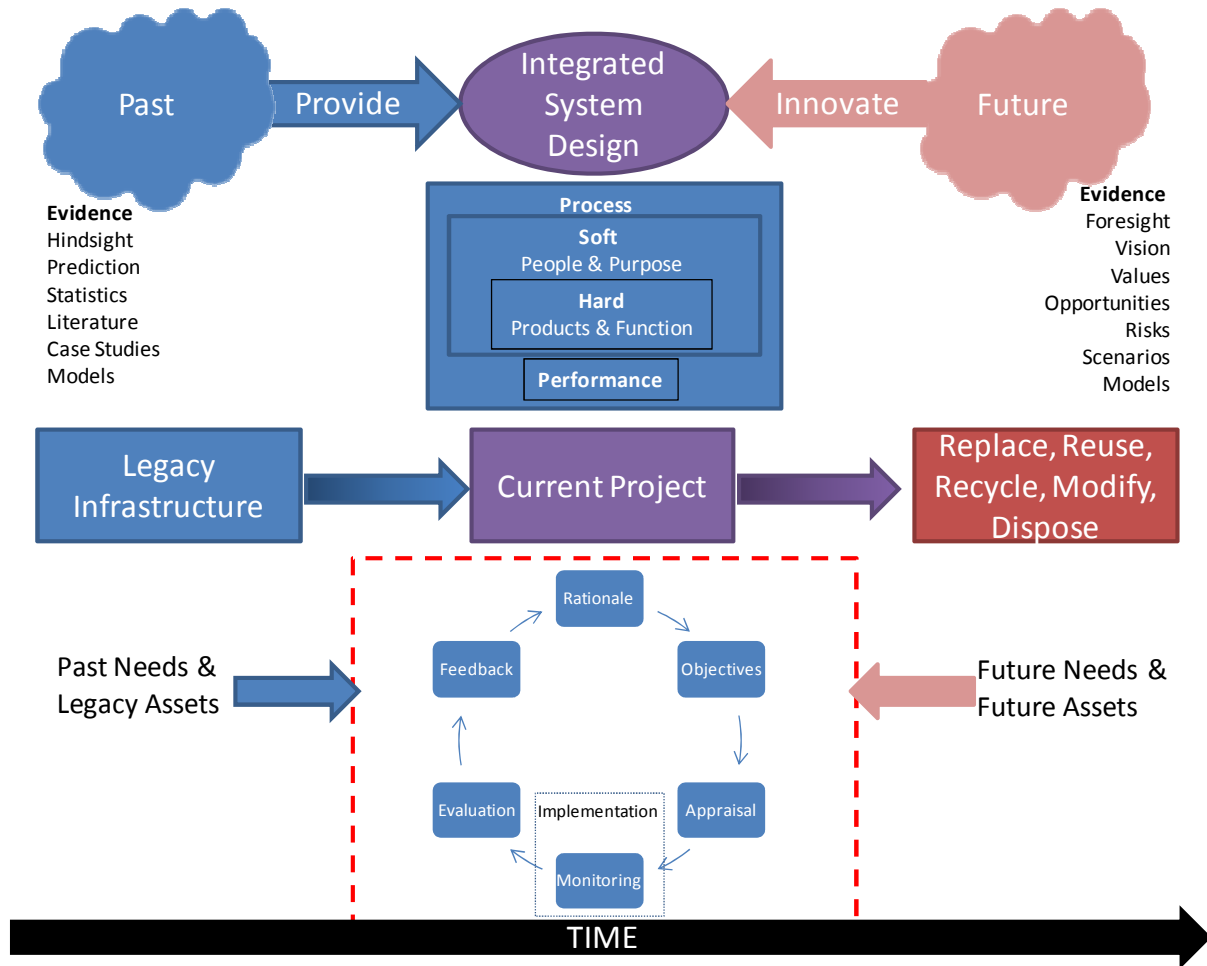


Figure 1. Schematic of interdependency Planning and Management Framework.

### III. Case Study Applications

#### IV. A. Phase 2 of the UK's High Speed 2 Rail Project

Background: The lack of capacity on the UK's railway network routes presents a major transport and economic development issue for the UK Government. The High Speed 2 (HS2) rail project<sup>5</sup> is being proposed to increase public transport capacity linking major urban areas in the North of England, the Midlands and London. The economic case for a high speed rail solution is built predominantly upon travel cost savings. The political case rests in part on an expectation that new infrastructure will also promote economic growth in the North of England, thereby contributing to a geographic 'rebalancing' of the UK's economy. The case study investigated beneficial *engineering* interdependencies along the planned HS2 routes from Birmingham onto Leeds and Manchester, with the aim of supporting the UK Department for Transport in scoping the route consultation.

**Method:** A workshop was held to engage participants from four different infrastructure sectors: Energy, ICT, Water and Transport. This provided a means to engage with relevant stakeholders and explore the context and boundaries to the HS2 Phase 2 project in an open-systems manner, and hence link HS2 assets and operations to the UK's policy context across multiple sectors. A matrix-based approach was used to structure the exploration of interdependency, and to identify innovative options to enhance the core rail project. Following this, participants were asked to compile an assessment of the evidence, both in support of and against the interdependencies, using a PESTLE-based tool. Necessarily this assessment of opportunities was cross-sectoral, broad ranging in scope, and qualitative, although numerical data was gathered where this existed.

**Results:** Twenty four potential interdependencies between the HS2 Phase 2 project and other infrastructure sectors were identified. (An example of the output from the workshop is presented in Figure 29 for the Water Sector-HS2 interdependencies.) Of the 24 interdependencies, five, were identified as being of high significance:

- Using High Speed 2 Phase Two corridor to provide additional electricity distribution capacity into Sheffield and Manchester. Combining HS2 Phase 2 with projects to enhance electricity distribution would consolidate and reduce visual blight and disruption during construction, though there would be issues over ownership, legislation and regulation. Economically, a single integrated project may be favourable as the total cost would be less than for two separate projects (e.g. for planning, consultation and tunnelling), and it would support and align increased economic activity in these regions. In social terms, city regions are expected to grow, with the expectation that HS2 would also contribute to stimulation of population growth. Additional and diverse routing of the electricity network should also improve its resilience.
- Using High Speed 2 Phase Two corridor to provide a bulk water transfer route between the north and south. Schemes for the bulk transfer of water from North-West England, where there is abundant rainfall, to South East England have been proposed in the past. Most recently United Utilities proposed a £2.6 billion North-South water pipe using the route of HS2<sup>28</sup>. However, cost estimates suggest this would be an expensive solution compared to alternatives, added to which 25-year water resource plans delivered under the UK water industry regulations suggest such solutions should not be required during this timeframe. Although bulk water transfer would potentially enhance resilience to drought, it also has the disadvantage of increasing energy consumption<sup>29, 30</sup>, and there is the potential of such a co-located pipe bursting and forcing rail track closures. This interdependency although significant was therefore discounted at the workshop.
- Using High Speed 2 Phase Two corridor to provide the capability for inter-regional water transfer. From an economic perspective the pricing principles for trading across water regions are in place and such an approach could provide a cheaper alternative to other water resource development options such as local interconnecting pipelines. For example, some water supply regions tend to be weakest at their extremities, so transporting water from neighbouring areas with an excess of water resources would be rational from a whole sector standpoint. It would also add to the resilience of the total UK water supply network and from an environmental perspective it could help regulators balance abstraction licensing against supply needs. The concept of water

transfer between water companies and water supply zones has been explored by Water UK, and the United Utilities 55km, £120m bi-directional pipeline between Manchester and Liverpool (West-East Link Main) is an example of the recent development of this type of infrastructure<sup>31</sup>.

- Using High Speed 2 Phase Two corridor (and associated construction) to provide the capability for additional flood protection (see Figure 29). Such an approach could be of significant socio-economic value in terms of enhanced flood protection for householders and businesses, and of interest to insurers and government. Politically it would also be attractive if the HS2 Phase 2 project brought further benefits beyond the public transport sector. It was noted that a report by Engineering the Future<sup>32</sup> supports the potential for the use of railway embankments as flood defences, whereas a joint report by DEFRA and the EA<sup>33</sup> indicates that existing rail embankment designs are not 'fit-for-purpose' as flood defences though they may provide a partial barrier. While the proposal is technologically achievable, it would come at additional costs, and furthermore the dynamic effects in flood plains are uncertain, adding to uncertainties due to climate and land use changes. However, the workshop concluded that such a scheme could be feasible and would create an overall positive benefit for the UK.
- Using High Speed 2 Phase Two corridor to provide additional capacity for the distribution of ICT infrastructure (e.g. fibre optic cables). The principal value would accrue by helping achieve UK national connectivity targets with less disruption than installing new separate ICT infrastructure. This option could offer diversity to the UK's ICT network, and may in the short term simply require a level of provisioning for future installation of ICT hardware. Economically this opportunity could provide an efficient route, with low latency making the relocation of data centres outside London more attractive, and this in turn could create new job opportunities outside of the London area. It could also be used to boost rural economies along the HS2 route. A countervailing view was that the HS2 project may be too late to assist in achieving UK connectivity goals, and by the time the project is operational, the need for additional fibre cables may have been superseded by alternative wireless technologies such as 4G. Support in the literature for this interdependency includes reports by Frontier Economics<sup>24</sup> and OECD<sup>3</sup>.

	1	2	3	4	5
A	Climate Change	-	May result in increased rainfall in North & decreased rainfall in South	May result in increased rainfall in North & decreased rainfall in South	-
B	-	Flood Protection	-	-	Affects resilience of the railway

C	-	-	Intra-Region Transfer	-	-
D	-	-	-	Bulk Transfer	-
E	-	HS2 embankments provide opportunity for flood detention storage	Provide route for pipeline to strengthen interconnections between water supply zones	Provides route for North-South bulk water transfer pipeline	HS2 Phase 2 Rail Line & Route

**Figure 29. HS2–Water Sector Opportunities to Engineer Interdependency**

The interdependencies identified during this case study cross the traditional boundaries of infrastructure sectors, and developing them effectively requires the HS2 project to be viewed as more than the provision of additional rail capacity and reduced journey times, important as these aims are. The outcome from this research contributed to the HS2 Phase 2 Route Consultation<sup>5</sup> which states in paragraph 11.06:

*“We have been looking into whether provisions could be made along Phase Two of the HS2 network for other utilities such as water, electricity or integration with flood management schemes. This could further enhance the benefits brought to the country by HS2 while creating jobs and driving growth.”*

## V. B. Lower Thames Crossing

Background: The existing Dartford to Thurrock Thames River crossing is an important part of the UK’s national, regional and local road networks, but studies have found that the existing crossing acts as a ‘bottleneck’ during peak times. Added to this, a large number of urban regeneration projects are proposed for the Thames gateway area, and traffic forecasts predict the need for increased transport capacity across the Thames. As a result the National Infrastructure Plan 2012<sup>2</sup> has identified the Lower Thames Crossing (LTC) as one of 40 projects of national significance.

There is an obvious interdependency between the need for a new crossing and planned urban regeneration: the effectiveness of the existing and new crossings can impact on the delivery and success of these regeneration activities, whilst the regeneration itself places further demands on the existing and planned crossings. Nevertheless, the LTC project<sup>14, 36</sup> is primarily motivated by a projected traffic capacity problem and is expected to proceed largely independently from decisions involving the planned regeneration projects. It is also clear from documentation that the regeneration projects will proceed regardless of decisions surrounding the LTC project. Desirable and undesirable interdependencies may therefore emerge, and the IPMF was applied to help understand these and identify the potential to plan and design for beneficial interdependencies.

**Method:** The framework and tools were applied in a desktop study of reports and literature for the LTC and other the infrastructure and regeneration projects proposed within the region. A matrix map was used to capture systematically the cross-sector interdependencies which were characterised and evaluated in terms of PESTLE factors. The resulting model was used to explore the system boundary, understand the core needs and policies driving the LTC project, and to identify a broad set of stakeholders with interest in the potential interventions and impacts. The output of this desk study was presented to these stakeholders who were then given the opportunity to add interdependencies, re-characterise and re-evaluate them, and provide additional. The stakeholder engagement provided a richer understanding of the architecture of the systems involved, and an identification of conflicting or compatible needs and policies.

**Results:** Forty-eight high-level interdependencies were identified from the desk study. Some of these are only applicable if the crossing is placed in a particular location and takes a particular form (e.g. bridge or tunnel). Some are necessary for the crossing to function; others are potential interdependencies which could enhance the LTC or external projects; and some present risks for the LTC project. In line with current assessment criteria, the wider regional economic impacts of the crossing have been broadly considered, but there is little evidence that this has extended to a consideration of the project as a proactive ‘agent of change’<sup>19</sup>. The additional, potentially valuable interdependency opportunities include:

- Using Lower Thames Crossing structure to provide the capability for additional electricity generation. The specific nature of this would depend on the form of the crossing, but suggestions include using traffic vibrations, excess heat, photovoltaic cells or tidal mechanisms to generate electricity through the crossing structure, e.g. using the crossing structure to create a tidal lagoon for electricity generation<sup>14</sup>. As Figure 30 shows, some dependencies are necessary for the LTC to function (e.g. power for lighting), while others are potential opportunities (e.g. to generate electricity), or hazards and obstacles (e.g. large pylons).
- Using Lower Thames Crossing to provide a capability for cross-river distribution of electricity, telecommunications, water, and waste infrastructure elements. Such schemes would be relatively straightforward in engineering design terms, and could add value from political, environmental and social perspectives, as well as allowing for sharing of construction costs. Downsides include more complications in project delivery, and in shared asset ownership or access rights for maintenance and operation.
- Using Lower Thames Crossing structure to provide a capability for additional flood defences. This interdependency would require alignment of a flood protection barrier planned under the Thames Estuary 210034 project with the LTC at Gravesham to Thurrock. The benefits and risks of delivering both large-scale infrastructure projects as an interdependent structure would require additional investigation.
- Using recycled materials in the construction of the Lower Thames Crossing. This would create a construction phase interdependency between the LTC and other local and regional projects, i.e. other construction projects or the waste/recycling sector could provide materials for the road base or surface, and reciprocally, the LTC could make use of what would otherwise be wasted by-products. This might be in the form of recycled aggregate, building materials or even car tyres (as implemented on the A90 between Perth and Dundee<sup>35</sup>).



- Sharing resources between the construction of the Lower Thames Crossing and other local regeneration and National Infrastructure projects. This approach has the potential to deliver cost savings in the form of shared equipment, coordinated resource and supply chain management, and joint training schemes.

Overall, this case study showed that an ‘open systems’ perspective allows for greater consideration of the ways in which interdependencies could be ‘engineered’ into an infrastructure and deliver regeneration in ways that extend beyond those typically associated with mega transport projects.

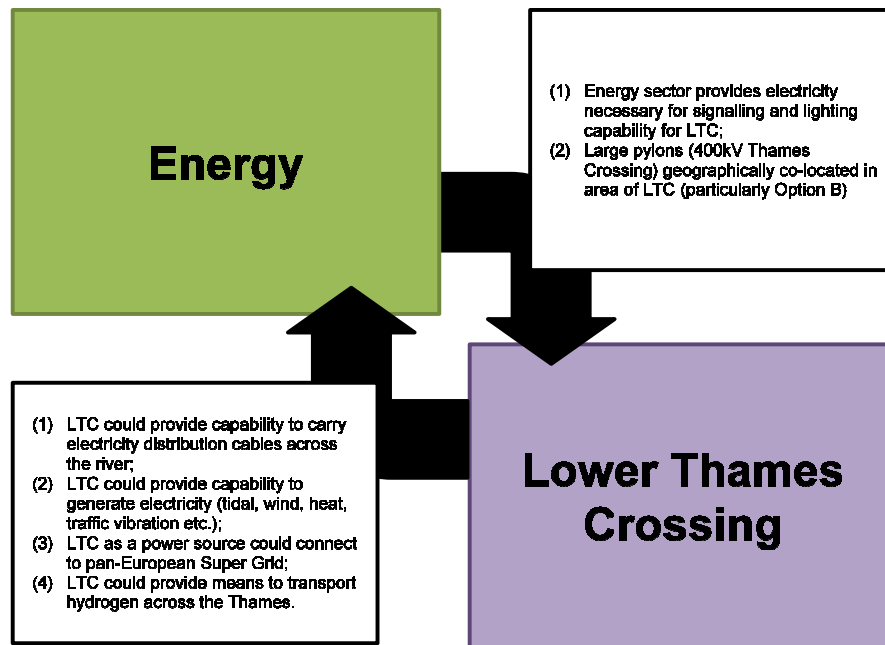


Figure 30. Energy Infrastructure & LTC Interdependencies.

## VI. C. Engineering the Future’s Infrastructure Timelines Project

Background: Engineering the Future ran a project to capture timelines for the next 40 years of UK infrastructure planning across five sectors: Energy, ICT, Transportation, Waste, and Water<sup>37</sup>. The IPMF was applied to identify areas where a lack of planning and appreciation of interdependency might be problematic, and where beneficial interdependencies might otherwise be overlooked.

Method: A workshop<sup>10, 37</sup> provided the means to bring together a diverse group of stakeholders from across the five timeline sectors, each with an interest in a relevant policy area or timeline project. It included representation from industry and academia, as well as those involved with governance. Initially interdependencies were identified *within each sector* between policies and the timeline projects. Following this, participants were challenged to identify and analyze interdependencies arising out of interactions present *across* all five timeline sectors, policies and projects. The inclusion of policy in this assessment brought a wider context to the interdependency mapping, including socio-economic and environmental needs. The information

used to develop the model came from project documentation, policies and plans, together with the domain knowledge of the workshop participants.

Results: Ninety-one interdependencies were identified<sup>10</sup> when analysing the relationships *within* each of the five sectors, i.e. intra-sector interdependencies. These comprise:

- Twenty-seven relationships within the energy sector spanning five projects and policies (Smart Grids, Exiting Building Use, Nuclear, Heating and Community Energy and Gas). The Smart Grid project (and associated policies) was identified as being a significant potential opportunity when integrated with the other elements, providing the means to optimise sector performance. It was also noted that achieving the potential benefits of Smart Grids was dependent on projects within the ICT sector.
- Fifteen interdependencies were identified within the transport sector projects and policies, four involving ownership and funding of the highways network. For example collaboration would be advantageous between the stakeholders seeking highways funding and those involved with managing airport capacity, HS2 rail and the London Gateway. Discussion also covered the interaction between national and local road usage, i.e. although night time use of motorways presents an underutilised asset, local policies restrict the nocturnal movement of freight. Collaboration to integrate and align policy in these areas could leverage underutilised assets and enhance a project's business case. It was also noted that the potential benefits from HS2 are not limited to the boundary of a rail project, but that wider benefits come from the potential transfer of traffic from the highways, hence contributing to the UK's emissions reduction strategy.
- Twenty five interdependencies were identified in the ICT and waste sectors combined. The emergence of 'Internet of Things tagging' (through RFID tags or QR codes) was revealed as a strongly interdependent technology with the potential for widespread benefits especially when integrated with other projects, e.g. recycling rare materials, the identification and tracking of suitable feedstock from waste for anaerobic digestion, and the location and classification of spatially distributed assets, including satellites. The effectiveness of this emerging technology is itself dependent on a resilient and capable broadband connectivity with nationwide coverage.
- Twenty four interdependencies were in the area of water infrastructure, including abstraction consenting and the natural environment, bulk water transfer, flood protection, infrastructure resilience, rainfall run-off and water treatment. For example, flood waters could be transferred and used for bulk supply, to recharge aquifers, with long-term implications for abstraction and the natural environment.

A further eighty-four interdependencies were identified when assessing interactions *between* the five sectors, i.e. inter-sector interdependencies. Figure illustrates the number of dependencies or interdependencies that were identified *within* and *between* the sectors. It shows the high density of interaction between the ICT and Transport sectors, and between the Energy sector and all other sectors. The following points summarise the main findings:

- Strong relationships between ICT and transport sector projects, with transport relying heavily on ICT to operate efficiently and effectively. Specific interdependencies identified include opportunities to reduce the need for physical travel by enhancing ICT capability (e.g. ubiquitous videoconferencing); the co-location of assets such as laying cabling alongside transport corridors; and information management and control services (e.g. route planning, transport management systems, congestion charging and enhanced train management to increase network capacity).
- Strong coupling between the energy sector and each of the other four sectors, with energy obviously playing a role in underpinning operations in the other sectors. Other specific interdependencies identified in this area include: Smart Metering impacting on energy usage; energy distribution and transport assets sharing physical space; opportunities to harness waste vehicle heat from tunnels; the energy sector providing fuel and lubricants for transport; transport of solid, liquid and gas fuels; and potential interactions between shale gas production and water abstraction and wastewater treatment.

Energy (44)	5	4	2	5
7	ICT (33)	8	4	4
8	3	Transport (39)	4	4
7	0	4	Waste (25)	3
6	2	4	0	Water (28)

**Figure 4. Density of Cross-Sectoral interdependencies for Timelines Project.**

## VII. Conclusion

The importance of interdependency management is beginning to be widely recognised by government, businesses and academics. This is evidenced in recent reports commissioned by the UK Government on nationally significant projects such as the recent HS2 Phase 2 consultation<sup>5</sup> and the Frontier Economics report<sup>25</sup> on systemic risks and opportunities.

If infrastructure providers are to generate opportunities and benefit from the interconnectedness of infrastructure networks and the environment in which they are embedded, then new planning and engineering approaches will be needed to analyse and create beneficial interdependent relationships. Integration of transport infrastructure is one long-standing example, illustrating both the challenge of complexity and the potential value from harnessing interdependency. Other examples of potentially beneficial infrastructure interdependencies have been identified in this paper.

Due to the highly interactive way in which people use infrastructure, it is important to be able to identify and model not just discrete infrastructure components in isolation, but also the interconnections, and recognizing this comprises the core of interdependency identification and modelling. The evidence from literature such as the OMEGA Centre research into mega-transport projects<sup>17-19</sup>, clearly indicates the need for engagement and involvement with a wide range of stakeholders early on in the project lifecycle, before the project is committed in terms of definition and scope. The research is also strongly supportive of open systems approaches, with a central focus on the importance of understanding the context in which proposed infrastructure is to be developed, and the transformative, co-evolutionary nature of such large scale developments.

Although design of positive interdependencies cannot be achieved by a simple mechanistic process, a range of existing systems engineering or systems architecting tools exist which have a long-standing applications in the design of complicated aerospace, marine, ICT and rail industrial sectors. The potential usefulness of such tools has been illustrated in this paper by the application of a matrix-based mapping tool to planned UK National Infrastructure. Implementing a structured and systematic search for interdependencies in this way has the potential both to challenge and complement existing planning and engineering practices in the design of infrastructure provided the transfer to this new application area is tested and reflexively developed.

The description of the IPMF process developed under contract to HM Treasury has been presented, together with an implementation of this based around a PESTLE and matrix mapping toolset. The elements of the framework have been demonstrated in three major case studies and found to provide an acceptable and intuitive approach by the stakeholders participating in the associated workshops. It should be noted though that a wide range of other tools exist that could be used to implement the framework. The key achievement for the interdependency framework and toolset developed under this project has been to develop an approach that facilitates innovation, but which is also intuitive and readily applied across sectors and academic disciplines.

The further conclusion reached from this research was the importance of bringing together stakeholder views from a broader community than would normally be consulted, if a more creative assessment of interdependencies is to be effected. In particular, this is based on the evidence from the contrast between the desktop based reviews of interdependency and those of the case studies based on workshop interactions. The pitfall of a desktop-based review of interdependency is to pursue an insular planning approach that will do no more than: a) catalogue well-known interdependencies as established on similar previous projects and simply apply a scalar to these patterns of development; and b) to do this with a disciplinary bias towards the negative, risk aspects of interdependency.

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# Modelling and Data Frameworks for Understanding Infrastructure Systems through a Systems-Of-Systems Lens

Matthew J. Berryman<sup>a\*</sup>  
Rohan Wickramasuriya<sup>a</sup>  
Vu Lam Cao<sup>a</sup>  
Qun Chen<sup>a</sup>  
Pascal Perez<sup>a</sup>

**Abstract:** Modelling and analysis of large systems of infrastructure systems carries with it a number of challenges, in particular around the volume of data and the requisite complexity (and thus computing resources required) of models. In this paper we present an integrated land use–transportation model of a region in Sydney, and detail how we integrated an agent-based model of location and transport choice with a traffic micro-simulator. We also discuss both some novel architectures for scalability of modelling as well as for fusion and relevant visualisation of large data sets. We have a particular focus on geospatial infrastructure data visualisation.

**Key words:** Transportation; Land Use; Geospatial Visualisation; Modelling.

## I. Introduction

Here we first introduce why we use agent-based modelling, then discuss the types of traffic simulation we considered, then review existing / incomplete modelling platforms for integrated land use – transportation planning, before moving on to a description of our model. There are two key systems we consider: land use (liveability and location choice), and the transportation system; in integrating these we provide a systems-of-systems perspective on the interplay between both.

### A. Agent-based modelling

In agent-based modelling, an agent consists of:

1. A list of things that comprise its state. This might include things like age, income, a list of friends / family, etc.
2. Rules for updating the state of an agent, usually in relation to other agents and the agent's general environment.
3. Rules for updating the rules (agent learning / evolution).

Agent-based modelling allows one to effectively capture a very rich set of complex behaviours and interactions, and is therefore highly suited to modelling complex phenomena. It has gained extensive use in the fields of economics<sup>1</sup>, social science<sup>2</sup>, ecology<sup>3</sup>, and biology<sup>4</sup>, amongst many others.

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<sup>a</sup> SMART Infrastructure Facility, University of Wollongong, Wollongong NSW 2522, Australia  
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Since we are interested in modelling the heterogeneous nature of liveability perceptions and location choice across a population, agent-based modelling provides the best framework for considering this in different land use – transportation scenarios.

### **B. Traffic simulation.**

Traffic simulation is a technique wherein vehicle movements through the traffic system are replicated by computer software. The state of the system is then estimated from the aggregated performance of all simulated vehicles. There are two main types of traffic simulation:

- In macro-simulation vehicles are represented as a traffic stream or platoon. The level of congestion on the road and the presence of traffic signals govern vehicle speed. Unlike macro-models, macro-simulation is able to deal with queues and intersection delays, making this better suited for analysis of congested urban streets and arterial roads.
- In microscopic simulation, individual vehicle units are traced through the traffic network. The movements of an individual vehicle are governed by how it interacts with vehicles in its proximity, for example car following models, lane change models, and gap acceptance models, providing granularity in vehicle-to-vehicle interactions not possible in macro simulation.

Since simulation models describe a dynamic process, they can be used to analyse a wide range of traffic problems when:

- Mathematical treatment is infeasible due to its spatial or temporal scale, or the complexity of traffic flow.
- Mathematical formulations represent dynamic traffic control environments as simple, quasi steady state systems.
- There is a need to view vehicle animation displays to gain an understanding of how the system is behaving in order to explain why the results were produced.
- Traffic performance needs to be understood prior to large investments in transportation infrastructure, e.g. what is the optimal geometric design of new entry/exit ramps.

There are two broad categories of traffic simulations:

- Highway: concerned with speed/flow/density relationships; lane utilisation; congestion ('shockwave' propagation); and
- Urban: with smaller areas involved and higher vehicle densities, these are more concerned with queue lengths, queue discharge speeds, travel times, delay times.

Given the above differences, and our focus on small urban regions, micro-simulation provides the best framework for our model, as well as providing an easy alignment between the agent-based model and micro-simulation, since there is a one-to-one mapping between individuals and cars in a household and entries in the TRANSIMS inputs, in addition to public transport vehicles.

### **C. Review of existing integrated land use – transportation models**



Here we review a number of existing models / attempts at an integrated land use – transportation model, and where they exist we discuss how our model differs:

- *UrbanSim*<sup>5</sup>
- *SimTRAVEL*<sup>6</sup>
- *ILUMASS*<sup>7</sup>
- *ILUTE*<sup>8-10</sup>

Essentially though, the key novelty of our research is to combine an agent-based land use model with a micro-simulator model of traffic.

*UrbanSim* does not have a transport simulator component, rather it provides only a framework for coupling to a transportation model, and this has been done with transportation models like *EMME*<sup>11</sup>. *EMME*, however, is a macro-simulator, thus is not suited for our purposes.

It is not an agent-based model, so while it has descriptive power and can (within the usual constraints and limitations) make predictions, it has very little power to explain why different demographics act the way they do in particular scenarios (other than to re-iterate the generic features of behaviour that went into describing the rate equations). More recent coupling attempts include *MATSim*<sup>12</sup>.

In *SimTRAVEL*, access to transportation and results from the transport simulator (like congestion and travel time) are the only drivers of land use demand. Although it does have a traffic simulator, this is a mesoscopic simulator, Malta<sup>13</sup>, and therefore will not capture the dynamics at a sufficiently low level of scale to be able to assess different light rail alignments and their impact on traffic and land use patterns. Besides, *SimTRAVEL* uses a software, called *PopGen*, to create a synthetic population, based on an Iterative Proportional Updating (IPU) approach<sup>14</sup>. While some attempts have been made to adapt *PopGen* to the Australian context, we found that its heavily US context-driven data management and approach were not optimal in a data-rich Australian context. We preferred to use a Synthetic Reconstruction approach<sup>15-16</sup>.

There are several projects that do combine, or did/will try to combine, an agent-based model with a micro-simulator, the *ILUMASS* project and the *ILUTE* project.

The *ILUMASS* project sought to bring together a land use model and a transportation mode, however unfortunately failed to get off the ground, due to having two sub-groups, one from a land use background, the other from a transportation background<sup>7</sup>. Our team had the advantage of a single team from a modelling background, drawing on expertise on both the land use and transportation backgrounds. The other reason that *ILUMASS* failed was in trading off scientific realism for modelling complexity, something that our team struggled with at times. In the end, the main one was around transportation complexity. Although micro-simulation is very detailed, that detail brings with it time complexity of the software (the time taken to simulate all of the traffic movements).

The *ILUTE* (Integrated Land Use and Transportation) project has been progressing well, but has not focussed on individual decision making around housing much, and in particular omits

some of the key drivers of and a module around liveability, which is a key requirement of our project and broader research.

#### **D. Background to the SMART integrated land use – transportation model**

The SMART Infrastructure Facility has developed an agent-based model of the South Randwick area that demonstrates the complexities of urban renewal and transit-orientated development. The agent-based modelling approach is adopted as it has the capacity of simulating the actions and interactions of autonomous agents (that is individuals or collective entities such as households or institutions) with a view to assessing their heterogeneous effects on the system as a whole. We have built a simulation model that can re-create *in silico* the observed complexity of urban systems, and generate—often unexpected—emerging patterns of social responses to changes in public policies or infrastructure assets. The model incorporates the following components: street network, public transport lines and timetables, traffic flow, land rates, population growth, individual travel routines, liveability factors, and the link between urban development and transportation options. The individually perceived liveability which forms the basis for the agents' decision making of movement comprises of factors such as housing costs, population density, socio-cultural diversity, available amenities and transportation options. The modelled agents include individuals and households living in a given area, land-use and transport planners, land developers, and transport operators.

The model simulation starts by building a 'realistic' population of around 110,000 agents for the City of Randwick and Green Square precincts (baseline population). This population then evolves over a (typical) 20-year simulated period, with models built to simulate birth, death and marriage/*de facto* relationship formation and breakdown. We also consider changes to employment status and, importantly for our model, changes to the number of vehicles per household and changes to travel diaries, driven by this evolution. To be realistic, the baseline population adequately matches the distribution of individuals and households living in a given area as per the demographics information provided by the Australian Census.

Beyond its statistical validity, this artificial society also displays decisional and behavioural patterns, based on individual perceptions of liveability in consistency, with empirical evidence from a survey and the literature. Traditional transport models consider individual attributes such as age, education or income, as well as household-level characteristics to account for the diversity of transport. The novelty of the new SMART model lies in combining a travel model with a model of land use, in an agent-based framework, allowing agents to incorporate information about present and future availability of housing stock type, parking facilities, recreational amenities and shopping conveniences. This new flexibility allows for a large range of future scenarios to be tested, e.g. social responses to specific land-use or transport policies.

## **II. Liveability**

Following Fernandez and colleagues (2005)<sup>17</sup>, we drive our residential mobility model through a dynamical model of perceived liveability. The conceptual structure of our liveability model is synthesized in the diagram below. From a subjective perspective on liveability, individuals tend to shape their preferences according to six factors describing various aspects of living conditions: (1) home, (2) neighbourhood, (3) transport, (4) entertainment, (5) services and

(6) work. Each factor can be described through a series of attributes. The mix of attributes and their associated valence (e.g., an attribute can be perceived negatively or positively) depend on individual perceptions.

In order to implement a decisional process we propose to adapt the conceptual model proposed by Lindberg and colleagues<sup>18</sup> for residential (re)location. The model assumes that a preference is established or a choice is made based on evaluations of the attribute level. For each factor, attributes are given even weights and they contribute equally to the overall valence of the factor. The factor level can be interpreted as a value/belief structure in which factors can be ranked and given different weights. According to Lindberg *et al.*<sup>18</sup>, for a given individual, factor ranking and attribute evaluation processes depend his/her life cycle stage, current location and peer influence. This was confirmed through empirical work<sup>19</sup>. Figure 1 shows the dimensions of liveability that our model considers. Our work on liveability provides details of liveability perceptions across demographic profiles<sup>20,21</sup>, which is used as input to the agent-based model, in conjunction with data we have on the areas in which agents can live.



**Figure 1: The six categories of liveability, and the aspects thereof, that our model captures.**

We have developed our model primarily to explore individual decision-making around liveability, and this depends on a good understanding of an individual's transportation options in an area. For this reason we need a traffic micro-simulator, as we discuss in the next section.

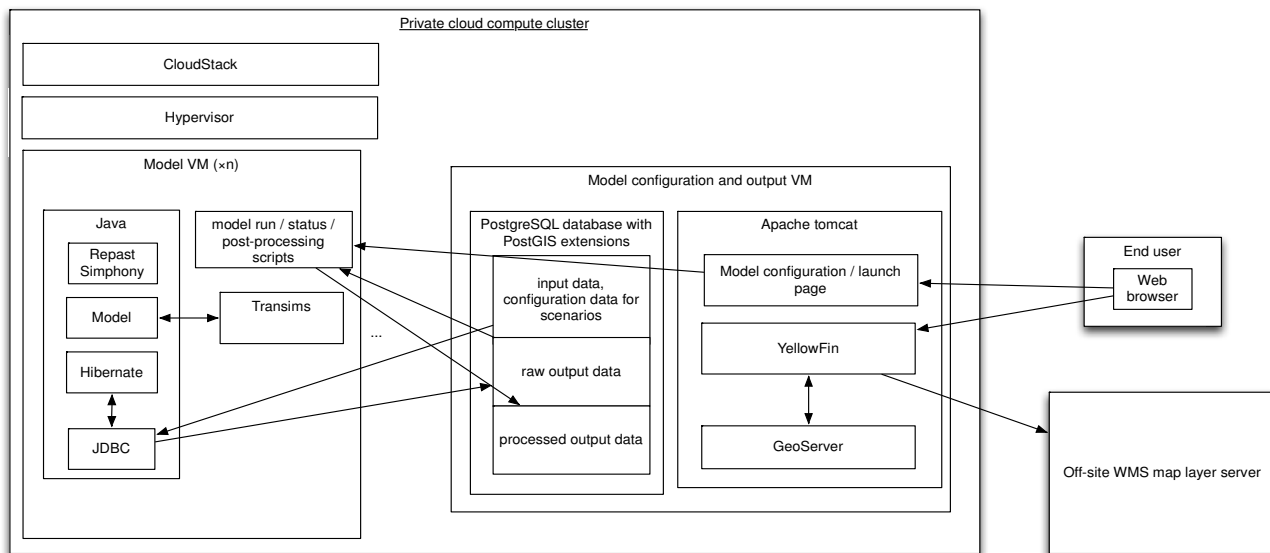
### III. Integration

#### A. Architecture

Figure 2 shows the high level architecture. There are documents we also hold for some of the lower level components that we've written as well as some documents around specification and testing. Note that there are a number of smaller Java libraries not shown. The architecture uses and has a loose coupling, with open standards where possible, between model components to allow for necessary evolution and future expansion of the software components.

The core of the model uses the Repast Symphony (sic) agent-based modelling platform, which was chosen as a good platform for building general-purpose agent-based models. We use it to load and schedule our agents (in random order, with a seed that can be fixed), as well as scheduling the running of TRANSIMS to simulate the transportation of agents. All of the above is packaged in a virtual machine (VM) running (Ubuntu) Linux, for the following reasons:

- There are a large number of different discrete software packages that need to be installed and maintained. Having them in a VM allows us to maintain a single, well-understood environment (such as the version of PostGIS), within which our software sits.
- Having a VM image allows easy deployment of a development environment to new developers.
- Having a VM image allows us to easily deploy to a private cloud for the purposes of Monte Carlo and/or multiple scenario simulation.



**Figure 2: Architecture, showing the end user, the private compute cloud running the model virtual machine(s) as well as a virtual machine running a temporary database for the configuration of scenarios and holding output data. Also shown is our data staging system for transforming this data along with other sources of data into processed data ready to be stored in a database and displayed on our dashboard web server. The CloudStack allows for simple web-based control of the model virtual machines, which run on top of a hypervisor (VMWare ESX in our case, due to its support for large numbers of nodes).**

We use a central database server to store input data, and in particular configuration data for the different scenarios (including any random number seeds for the replicates), intermediate data that we want to keep a record of, and model outputs. Having a centralised database server aids us in quickly spooling up multiple instances of the model from the same virtual machine image—each one in turn will load a different scenario as managed through the input database. The central database then captures all of the output data (allowing each VM instance to be small), ready for collection in our dashboard data visualisation and analytic system.

Within the model virtual machines, the Hibernate API effectively provides a layer of abstraction and better handling of the database queries of reading, manipulating and storing data. JDBC (and the accompanying PostgreSQL JDBC driver) provide the underlying database connectivity. The PostgreSQL database was selected due its support of SQL standards, ease of configuration, licensing (BSD-style), and importantly its support of geospatial information system (GIS) extensions, through PostGIS.

## **B. *TRANSIMS***

*TRANSIMS* was chosen as the traffic micro-simulator as, in its current iteration, it is a clean, efficient, C++-based (including good use of STL) platform that supports an individual (person and vehicle) level of modelling, and supports detailed microsimulation of traffic to support the requirements of our software, including but not limited to:

- road-by-road and minute-by-minute analysis of traffic patterns; and
- details of what individuals are going where on public transport, and analysis of usage (raw, and percentage utilisation).

We acknowledge the choice is not perfect, in particular we only use one run (with some limited annealing) of traffic simulation, as discussed below however we're only interested in a fairly coarse level of behaviour, and other concerns such as support (via Argonne National Labs) and our familiarity with it were also factors. We have a set of scripts (bash, and batch when running on Windows) that drive the execution of *TRANSIMS*, and we pass data to and from it via the filesystem (sets of text-based input and output files, plus the network files derived from the shape files for the road and bus networks).

The integration has been conducted by suspending the rest of the agent-based simulation, while execution of *TRANSIMS* takes place. Normally one would use a process analogous to simulated annealing to arrive at the solution; running the router to establish initial routes, then finding when vehicles jam, and either redirecting them off the street temporarily into a park (if the numbers are sufficiently low) or by then re-routing them using the router and then running the simulation until numbers jammed are sufficiently low. Given the typical travel volumes (around 100,000 commuters), and our desire to simulate a 20-year period, we are forced to run only one typical weekday and weekend in simulation per year, and run only one iteration of the router. We have compared this with test runs of multiple iterations of router and the core microsimulator of vehicle movements, and found that travel times are within 5%; this we consider sufficient for our purposes.

Agents in our model have the following properties:

- Age
- Gender
- Weekly income
- Membership in a household (including single person households)
- Occupation
- Highest education finished, and
- Critically, agents have a travel diary, synthesised from household travel survey (HTS) data, and with work journeys also drawn from journey to work data.

The method we are proposing for such an assignment comprises two major stages. The first stage deterministically searches in HTS data for households that best match the household type, number of children under 15 years old, and number of adults of a synthetic population household. The deterministic search carried out in those steps gradually relaxes the constraints on exact matching of the number of residents and exact matching of the number of children younger than 15 years old so that the search always returns at least one HTS household.

The second stage randomly selects a HTS household from the list of households from stage one and assigns travel diary of individuals in this HTS household to those in the synthetic population household. The random selection in this stage follows a uniform distribution.

The travel diaries are selected from HTS data at household level. This is because we wish to reserve the inter-dependencies (in terms of the sequence, travel times and purpose) of daily trips of individuals in the same household.

*TRANSIMS* by itself is a tool to simulate the travel behaviour of each agent throughout an entire 24-hour period. Therefore, in order to integrate with *TRANSIMS*, a synthetic population with agents' activities, which are their travel diary in another word, is essentially required.

In terms of travel diary, this is a set of all trips that an agent travels during a day. As a result, for each trip agent will need to provide for *TRANSIMS* their ID, the household ID that they belong to, the purposes of the trip (for instance, go to home, go to work, go to school, go shopping, go for social recreation or other purposes), the travel mode of the trip (for instance car, bus, train, bicycle, walk, or using carpool as a car passenger), the start time and expected arrival time of the trip, the origin and destination location of the trip. If agent travels by car, our software additionally provides to *TRANSIMS* which car in the house they are using (for instance the second car in the house) and where they park that car as well.

As a result, by using these input data and the road and transit network, *TRANSIMS* will simulate the travel behaviour of each agent throughout 24 hours of a day in order to conduct analyses of agents' interactions so that agents are traced for every second of the day. Therefore, the location of each agent, car or transit vehicle is known for every second of the day as well as the traffic flow and congestion are provided.

Based on these output data, the Sydney model collects the travel time of each trip, using them

to calculate the travel cost of the trip by using the current travel mode and other travel modes. Agents, based on these costs, will make their own decision about their travel mode for their trips in the next time step. Our model also utilises the congestion statistics from TRANSIMS output to calculate the satisfaction for agents to make a decision of relocation (staying or moving out the study area).

### **C. Output dashboard analytic and visualisation software**

The dashboard system comprises:

- The centralised database that holds raw data outputs from the different model runs across the model VMs; and
- ETL (extract, transform, and load) functions on the output database server
- A server running the *YellowFin* data analysis and visualisation platform, including the web front end.

All of these are outlined further below.

We have a database server that holds a variety of infrastructure databases, processed model output databases, and a metadata database that holds all of the metadata associated with all of the other databases as well as descriptions, input data, and configuration details of all of the model runs.

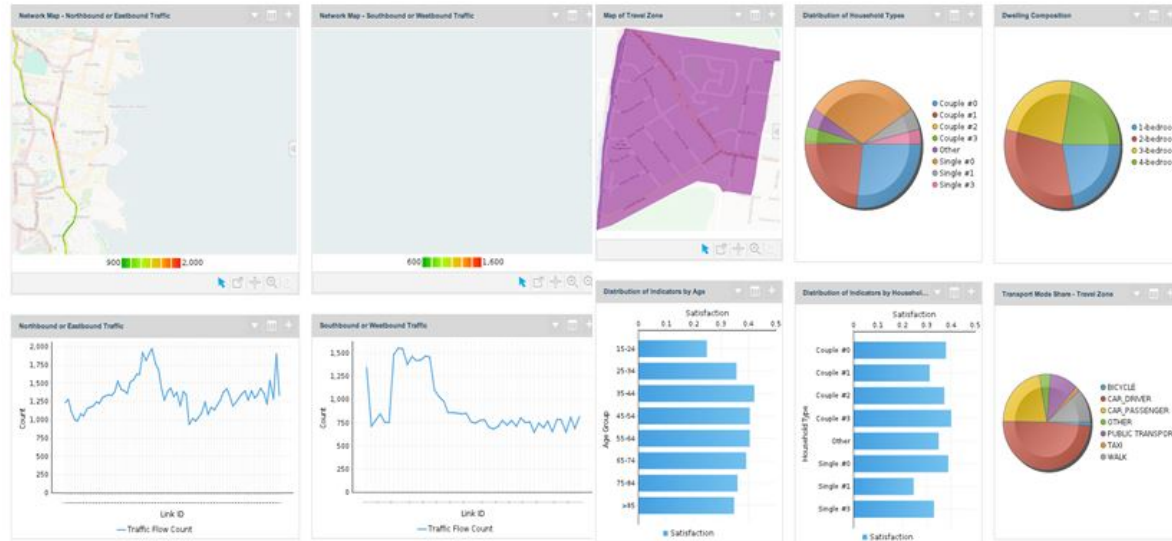
Raw data from the model outputs is transformed using custom ETL functions, which as the name suggests is where the data is extracted from the raw data database, transformed into a form suitable for use in the dashboard. In particular this means use of star schemas for performance and other reasons as below, as well as performing any necessary statistical / summary transformations, which also leads to good performance of the dashboard front end.

We use a schema following the star schema design method for the transformed data, for the following reasons:

- Star schemas are simple to understand
- They provide excellent query performance. In particular, using star schemas avoids costly joins, sorting aggregation, etc.
- Hierarchies, levels and attributes exist in one place; and
- Conformed dimensions can be reused.

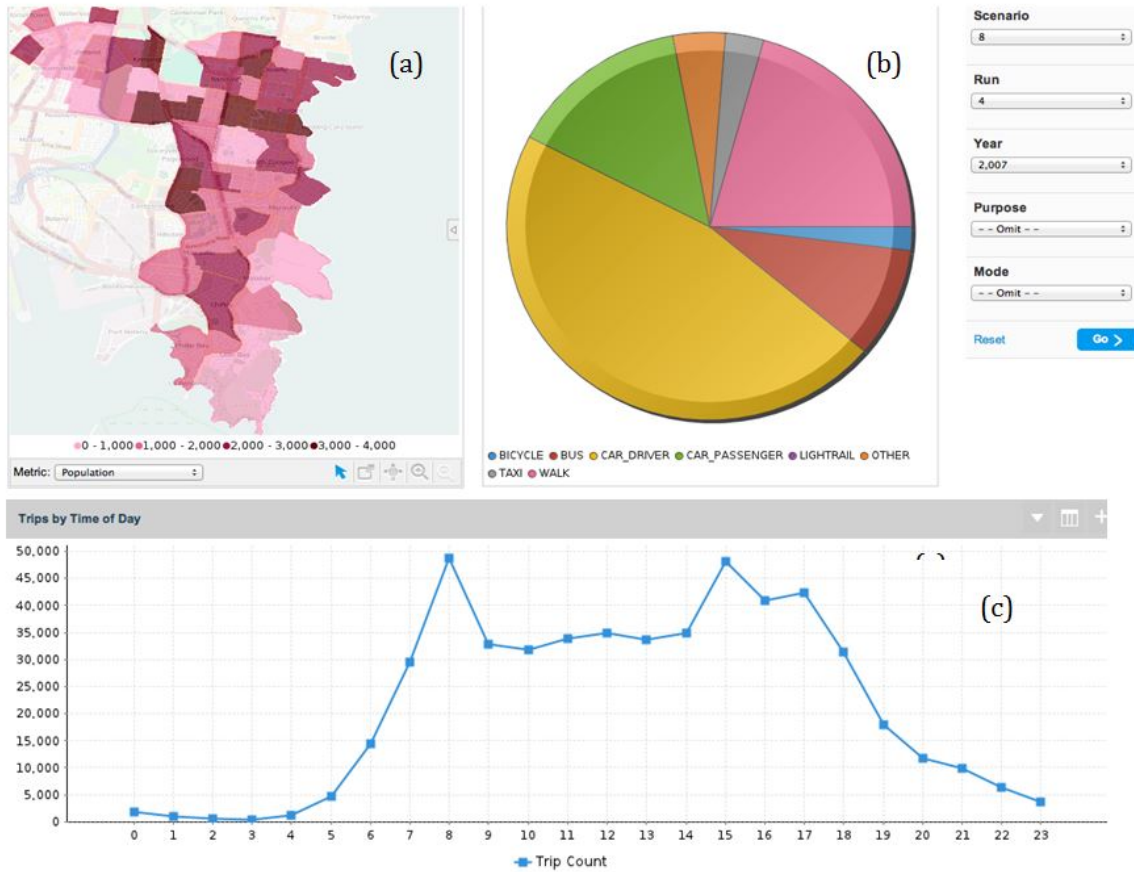
*YellowFin* is a business intelligence package that supports rapid development of graphs and other analytics around a set of defined outputs. One key aspect of *YellowFin* that makes it stand out from the rest of the business intelligence software packages is its excellent capability to handle geospatial datasets including vector (point, lines and polygons) and raster data. We benefit from this capability by using mainly *YellowFin*'s mapping to generate highly interactive map-based reports that are used as stand-alone reports or as embedded reports in dashboards. *YellowFin* supports Web Mapping Services (WMS) from *OpenStreetMap* tile servers to enrich those map-based reports. We use *GeoServer* to serve various ancillary spatial data as WMS layers that are then accessed by *YellowFin* map-based reports.

Different web dashboards, and reports (viewable from the web site, or sent via email) can be set up to allow point and click analysis of model data by end users. These can be re-used across different model scenarios. Figures 3 and 4 show a variety of outputs from our model, as displayed on our dashboard web site, with the output data from an early validation run of our model.



**Figure 3. (left) The web-based dashboard for a road, showing traffic density along the route, by map and by road segment in northbound and southbound directions. (right) The web-based dashboard for a travel zone, showing a breakdown of household types, satisfaction with the area by age, and the distribution of dwelling capacities (1, 2, 3, and 4+ bedroom dwellings), for the area of Sydney shown in the map.**





**Figure 4. Summary statistics for a whole study zone for 2007, featuring (a) population density, (b) transport mode share across all purposes (mode share for particular purposes can be selected), (c) trips by time of day.**

#### IV. Discussion and Conclusions

We have successfully integrated a traffic microsimulator (*TRANSIMS*) with an agent-based model of liveability and location choice, however some further work to do on validation is required. To date our model of population evolution, starting from 2006 ABS (Australian Bureau of Statistics) Census data, has been validated against 2011 ABS Census data, and traffic has been validated against both traffic count data and congestion data with some measure of success on main roads, though future validation will need to be done after some corrections on more local streets.

The integration of the *YellowFin* BI layer provides a useful and flexible means for visualising outputs from both the broader ABM as well as from *TRANSIMS*.

Our model successfully reproduces some key dynamics of the interplay between transportation and land use, and in future work we will present the completed validation and results from different scenarios.

### Acknowledgements

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# **Modeling Framework For Regional Integrated Simulation Of Transportation Network And Activity-Based Demand (Polaris)**

Joshua Auld<sup>a</sup>  
Michael Hope<sup>a</sup>  
Hubert Ley<sup>a</sup>  
Bo Xu<sup>a</sup>  
Kuilin Zhang<sup>a</sup>  
Vadim Sokolov<sup>a\*</sup>

**Abstract:** Travel demand, traffic flow, network operations and land-use models are typically modeled in a decoupled way, i.e. each of the components is modeled separately assuming the others are fixed. Moreover, the models are often developed by different groups for different contexts, requirement, etc. In this paper we present a prototype of a software framework which allows the user to develop an integrated simulation of a transportation system in a standardized, extensible manner, as well as an implementation of an agent-based planning and network operations micro simulation model using this approach. The project uses an agent-based modeling approach to developing an integrated transportation system model. This allows the model to overcome some of the limitations of traditional aggregated transportation models, particularly with respect to sensitivity to behavioral aspects of the travelers. POLARIS project, then, is intended to develop such an modeling framework and demonstrate the benefits of this approach through the implementation of an integrated travel demand and network operations agent-based micro simulation model. The model is intended to be used in evaluating network operations improvements and ITS implementations from a planning perspective. This paper provides background on the POLARIS modeling framework and details the development of several modules using the framework which form the basis of the planning and operations simulation model.

**Key words:** Integrates transportation simulation; Agent-based; Modeling framework; ITS infrastructure; Traffic operations.

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<sup>a</sup> Argonne National Laboratory, Argonne, IL, 60439, USA

<sup>\*</sup> Corresponding author: Vadim Sokolov [vsokolov@anl.gov](mailto:vsokolov@anl.gov)  
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## **I. Introduction**

Since the initial development and deployment of Intelligent Transportation Systems (ITS) there has been a need to evaluate the impacts of ITS investment on the transportation system, as for any other system investment, which has often been done using simplified sketch planning tools that rely on existing macro demand model, such as IDAS<sup>1</sup>, or a Cube-based ITS tool developed for Florida DOT<sup>2</sup>. Also, USDOT developed the integrated corridor management analysis, modeling, and simulation (ICM AMS) methodologies that assume combining macroscopic travel demand model with meso/macroscopic traffic flow simulation to test impact of different ITS technologies<sup>3</sup>. Another approach used is to combine existing general purpose modeling tools to evaluate limited aspects of the system<sup>4,6</sup>. Dynamic traffic assignment is often the core methodology for both off-line evaluation of intelligent traffic operational planning and on-line traffic control and management of the Intelligent Transportation Systems. Peeta and Ziliaskopoulos<sup>7</sup> provide an excellent survey of the DTA models in terms of analytical and simulation-based approaches, and point out that the simulation-based DTA models have gained greater acceptability in the context of real-world deployment.

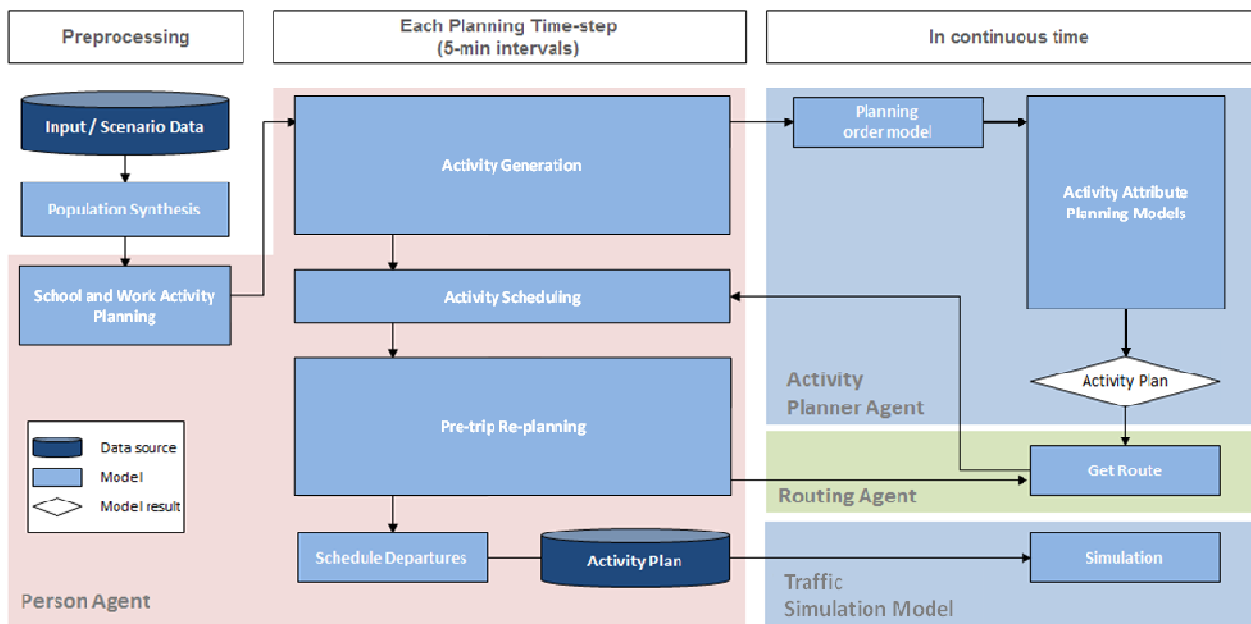
## **II. Activity-Based Travel Demand Model**

Travel demand is estimated in POLARIS by using an activity-based demand model. The demand model is agent based, meaning that the individual agent actions and behaviors are simulated. The demand behaviors modeled include time-dependent activity generation, activity attribute planning and replanning, and a detailed activity scheduling model, which resolves schedule conflicts and maintains a consistent daily schedule for the agent. The demand components, including activity generation and activity planning, are also responsive to network and traffic management events, which can result in agent replanning. The demand components implemented in the POLARIS derive from previous work in modeling activity-planning and scheduling behaviors found in the development of the ADAPTS (Agent-based Dynamic Activity Planning and Travel Scheduling) model<sup>8</sup>. We have reorganized the ADAPTS model components to more closely fit the agent-based approach and have implemented them by using the POLARIS modeling language and framework. The ADAPTS model was originally developed to simulate the underlying activity and travel planning and scheduling processes that lead to observed activity-travel patterns. The model was designed to continuously integrate directly with traffic simulation, forming a fully dynamic model, with planning and scheduling occurring in a time-dependent manner and impacted by the results of the time-dependent traffic network. The model allows for the simulation of a wide range of travel-demand management policies, especially those which impact the planning process.

The ADAPTS model components have been implemented as a set of agents and sub-agents that perform events that generally represent a single model or process in the original ABM. In the demand model there are two primary executable agent types and several sub-agents. The primary agents are the person agent and the activity-planner agent, which represents the person agent's cognition of the activity planning process. The person agent has a variety of sub-agents, which represent various faculties of the individual. These include the perception agent; the planning agent that generates activities and handles planning or re-planning; the scheduling agent; the movement agent for interacting with the network model; and the routing agent, which interacts with the network model for making routing decisions. The demand model interacts with

the network model components through the person agent, by way of the movement handler agent and through the routing faculty. The agent schedules when these actions occur and executes the movement or routing methods of the network model. Similarly, the person interacts with the ITS model components through the perception agent, which updates the person's understanding of the network state based on the ITS action. The interactions between the various agents are shown in Figure 1.

The figure shows the primary connections between the agents as described above, the basic simulation process that each agent follows, and the time resolution at which the various discrete events are scheduled. The figure shows that most person agent events occur at regular recurring intervals, currently set to five minutes. The agent polls itself every five minutes to see whether any new activities need to be generated or any activity-travel plans need to be executed, etc. Many of the remaining agent events occur at a near continuous time resolution, however. Activity planning events such as the choice of activity location, mode, etc., as well as the scheduling of the activities, occur throughout the simulation, as do the routing and traveling.



**Figure 1. Demand model agent simulation framework**

### III. Simulation-Based Dynamic Traffic Assignment Model

The network model component in POLARIS is a one-shot simulation-based dynamic traffic assignment model that includes the following: (1) a route choice model, (2) a route generation model, and (3) a mesoscopic traffic simulation model. Each of these models is implemented as a collection of POLARIS agents and utilizes the discrete event engine to coordinate execution scheduling and run efficiently. We use two types of route choice model for one-shot DTA, one is

route choice based on pre-trip prevailing traffic information; the other is a bounded rationality based en-route switching model for modeling travelers adjust their route using real-time traffic information. We have a future plan to incorporate the DUE approach for an iterative DTA model.

The agents related to the network model are seamlessly integrated with the demand model agents by providing traffic information for travelers taking demand side actions. The ITS model agents are incorporated by publishing sensor information to the TMC for making traffic operations and control decisions. In turn, the demand side actions and TMC's operations and control decisions also impact the traveler's route choice and traffic flow pattern.

In POLARIS, the network model includes three categories of agents: traveler agents, routing agents, and traffic simulation agents. In the route choice model, routing aspect of the traveler agent is modeled, the route choice decisions are made with respect to its own user characteristics in response to pre-trip and/or en-route traffic information and events from the Internet, variable message sign (VMS), global positioning system (GPS), and radio. A bounded rationality based en-route switching model<sup>9-11</sup> is implemented by the routing agent. The routing agent is used to calculate the least time routes for individual traveler agents. This calculation employs simulated travel costs. The traffic simulation is conducted by three agents, which represent the overall network, the link, and the intersection. Together these agents perform the task of simulating each individual traveler agent based on the simplified kinematic wave theory of traffic flow<sup>12</sup>. A notable implementation of Newell's model is in an open source dynamic traffic assignment tool - DTALite<sup>13</sup>. In addition, an optional intersection control agent simulates signal controls such as pre-timed signals, actuated signals, stop signs, and yield signs. The traffic simulation model also captures dynamic capacity reductions due to events such as weather and accidents.

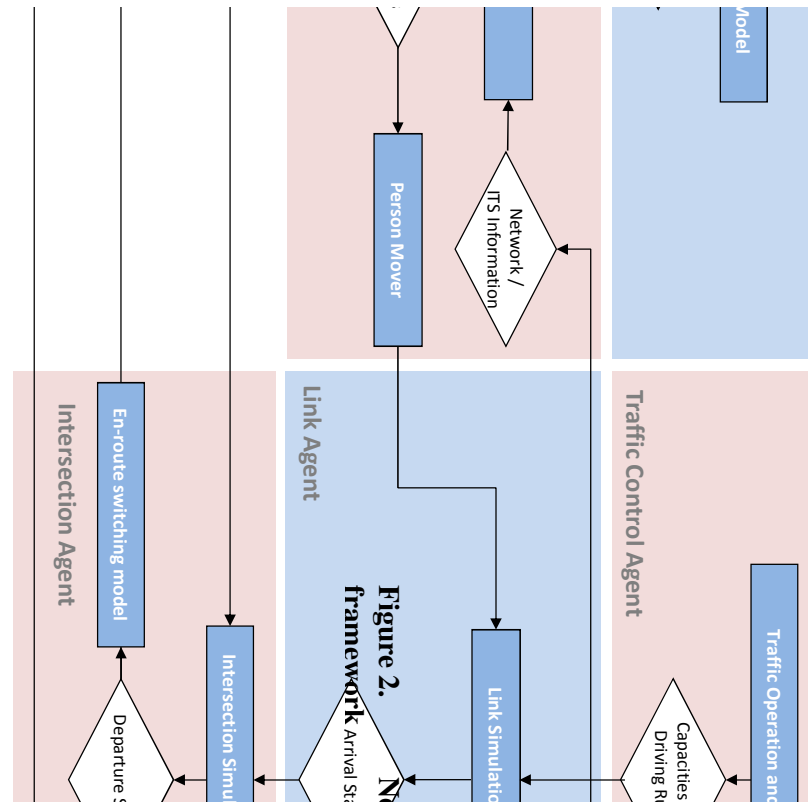
The interactions among these network model agents, as well as the demand model agents and the ITS model agents, are depicted in Figure 2. Given the inputs of activity plans determined by the demand model agent, each traveler makes route choice decisions on the basis of routes generated by the routing agent using the traveler's route choice behavior with response to information provided by the ITS model agent. These traveler agents with route choice decisions are then simulated by the traffic simulation agents. The output of the traffic simulation model is the network performance and traffic flow pattern, which will be inputs to the route choice model, demand model, and ITS model in POLARIS.

#### **IV. Intelligent Transport Systems, Network Events and Traffic Management Agent**

Currently, the major application of the POLARIS framework is the evaluation of ITS benefits. For that purpose, three components in the POLARIS were developed on top of the demand and network components: network events, ITS infrastructure, and traffic manager agent (TMA).

The ITS infrastructure is an input to the model. Currently, the following types of ITS components are supported: variable message sign (VMS), highway advisory radio (HAR), tow truck dispatch, open hard shoulder sign, and in-road sensor. The in-road sensor is used to model the locations for which the speed and volume data are available to the manager, either from loop detectors or from data vendors. The sensor model allows to estimate the value of available

information and to determine how it affects the effectiveness of the management decisions. All the sensors can be used to model noisy data; a user can specify the standard deviation of the measurement error for each of the sensors. Each HAR and VMS can display/broadcast a single message associated with a network event.



Five types of network events can be modeled by the network events manager: weather, accidents, congestion, lane closure, and travel time. Each event has special information about the area affected, start/end time, and event-specific attributes. For example, for a weather event the user can specify type (snow, rain, or fog), level of precipitation, visibility, asphalt conditions, etc. IBM's Smarter Cities incident representation semantics was used to model most of the network events in POLARIS.

The role of the traffic manager can be played either by a human or by a robot. Both of the approaches serve a different purpose. The human in the loop setup allows interaction with the ongoing simulation and hand-crafting the ITS response to a given scenario. This approach may be able to be used effectively for educational purposes or as a simulator-trainer for traffic engineers.

The performance of the transportation system and the benefits of ITS and traffic management need to be evaluated under many different assumptions. Treating weather, special events, road construction, and time of day as random variables leads to a large number of possible scenarios that need to be evaluated. It is error prone and requires significant amount of time to hand craft ITS response strategies to all possible scenarios. Thus, as a part of the framework an automated traffic manager agent is being developed. The goal of this agent is to monitor the status of the transportation network (speed, travel times, etc.) as well as network-related events (weather, incidents, etc.) and decide on a response that would mitigate unusual congestion levels on the



network. This aspect of the model is intended to allow planning agencies to analyze the benefits of different network operational improvements. Currently, the traffic manager has two roles. The first is to identify unusual congestion by observing the network performance from the ongoing simulation and statistically comparing the simulation data with the historical data. The second role is to each highway advisory radio and VMS sign to an event. To do so, the agent calculates a relevance score, which is a function that maps a pair (network event, VMS/HAR, etc.) to a score. The information on the event with the highest score will be displayed or broadcast. To calculate the relevance score, the agent uses statistical data from historical travel patterns (events on heavily traveled parts of the network will score higher) as well as event parameters (the more severe the event, the higher the score).

## V. Running cases

Another component provided in the base POLARIS framework (i.e., independent of any specific model implementation) is the scenario manager, a set of tools used to define, execute in parallel, and analyze various traffic simulation scenarios in terms of conditions such as weather, demand, incidents, and so on. The scenario manager allows the modeler to account for non-typical conditions (inclement weather, special events, and incidents) in evaluating the model response. Furthermore, it allows for the computation of MOEs based on the expected distribution of simulated scenarios. These features are particularly useful for benefit/cost analysis of ITS or other transportation improvement projects, where a significant amount of the expected benefits is incurred for non-typical conditions. The scenario manager follows the guidance provided in “Operations Benefit/Cost Analysis Desk Reference”<sup>14</sup> and “Guidebook on the Analysis of Active Transportation and Demand Management Strategies”<sup>15</sup> for scenario generation and analysis. In addition, it is able to exploit high performance computing resources, such as TRACC’s 92 node Zephyr cluster, to simulate multiple scenarios concurrently. The major components of the scenario manager are summarized below:

- Scenario generator - generates multiple scenarios based on a JavaScript Object Notation format scenario description. The scenario description defines scenarios using parameters such as weather conditions and incident types as well as the occurrence probability associated with each scenario.
- Scenario executor - executes scenarios as computing jobs in a computer cluster. The computer cluster automatically schedules and assigns the jobs so that they are executed on different computers in parallel. The scenario manager supports the PBS (portable batch system) job management system and works with Linux cluster environments.
- Scenario monitor - monitors the status of each submitted job, including the progress percentage, estimated remaining running time, summary of network statistics, and so on.
- Scenario analyzer - collects the performance measures reported for each scenario, assigns weights to them by their occurrence probabilities, and sums across scenarios to provide overall measures of effectiveness. The scenario analyzer also produces plots of performance measures from the outputs of scenario execution for comparative analysis.

The scenario manager provides two modes for generating weather/incident scenarios, namely, the comprehensive mode and the representative mode. These two modes differ in whether the

duration of the weather/incident event covers the entire simulated period and where the adjustments of capacity and free-flow speed are made. In the comprehensive mode, the duration of an event covers the entire simulated period, and adjustments are made to the link input. In the representative mode, an event occurs during a sub-period of the simulated period, and adjustments are made online by the network simulator. Each of the two modes has its advantages and usages. The advantage of the comprehensive mode is that the network simulator does not need to know how to model weather/incident events; the modeling knowledge is outside the network simulator, provided by the scenario manager. Thus, the comprehensive mode can be used by existing network simulators other than POLARIS. The advantage of the representative mode is that it can manage scenarios in which there are multiple events and each event has a temporary time scope. Therefore, the representative mode is suitable for scenarios with incidents.

Initial tests were run using the network simulation model to route and simulate 27 million trips in the Chicago metropolitan network over a 24 hour period. These tests were performed on one node of TRACC's Zephyr cluster, the system specification is as follows: two AMD 6273 2.3GHZ CPUs, 64G RAM, CentOS/Linux 6.2. The wall time for a multi-thread case is approximately 75 minutes.

## VI. Conclusion

This paper has detailed the development of a modeling framework and demonstrates the benefits of this approach through the implementation of an integrated travel-demand and network operations agent-based model. This model (Integrated ABM Simulator) is intended to be used in evaluating network operations improvements and ITS implementations from a planning perspective. Details have been provided about the POLARIS modeling framework and several ancillary tools used for model development, as well as a description of the Integrated ABM Simulator model developed using POLARIS.

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**FOR MORE INFORMATION  
PLEASE CONTACT**

Garry Bowditch  
Chief Executive Officer  
garry\_bowditch@uow.edu.au

Tania Brown  
Chief Operating Officer  
tania\_brown@uow.edu.au

Prof Pascal Perez  
Research Director  
pascal@uow.edu.au

Victoria Black  
Strategic Marketing Manager  
vblack@uow.edu.au

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